RECLAMATION OF FOREST LANDINGS IN THE SUB-BOREAL SPRUCE BIOGEOCLIMACTIC ZONE USING BIOSOLIDS AND FALLOW LEGUMES AND GRASSES

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Abstract

Organic matter amendment to soil provides a source of plant nutrients, improves soil condition, and minimizes disposal of organic waste materials in landfill. Reclamation of a compacted Gleyed Eluviated Dystric Brunisol was conducted using tillage, addition of a mixture of land stored primary clarifier waste and municipal biosolids (70 Mg/ha and 155 Mg/ha, respectively) following tillage, and seeding fallow legumes and grasses. Comparisons were made between plots treated with tillage and biosolids (with or without seeding), tillage only treated plots (with or without seeding), and control plots in soil properties including soil solution composition, bulk density, %C, pH, available NO_3-N and NH_4-N, C:N, base saturation, ECEC (displacement by $BaCl_2$ method), and total elemental composition (by mixed acid microwave digestion). Lodgepole pine *(Pinus contorta* Dougl. *ex* Loud.*)* seedlings planted in the study area were measured for foliar nutrient status, total height, basal diameter, needle length, leader height, and shoot weight. Seeding fallow legumes and grasses was not found to have a significant effect on soil properties of biosolid-treated plots. The cover crop failed to establish on tillage-treated areas. The pH, ECEC, total P, and total Ca of plots with biosolid treatment were significantly higher than those for tillage-treated and control plots. C:N and total Na of biosolids-treated plots were significantly lower than those of tillage-treated and control plots. Total K was largely unaffected by treatment. Soil solution Na and Ca were significantly changed by biosolid treatment relative to control plots and tillage-treated plots. Soil solution pH was significantly increased by biosolid treatment relative to control plots, but not in comparison to tillage-treated plots. Biosolid amendment did not significantly change seedling height, but seedlings planted on tillage-treated and unreclaimed landing (control) plots were significantly smaller than those of an off-landing plot.

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Chapter I – Introduction

A limited number of publications from across Europe, Canada, and the United States have documented the effects of landing and skid road construction on the physical, chemical, and biological components of forest soils. These changes in soil properties include features such as nutrient content, bulk density, hydrology, and carbon to nitrogen ratio (C:N). Such changes are long-lasting and reduce tree growth (Lenhard 1986, Hatchell et al. 1970, McNabb 1994).

Long-term observations frequently report that differences between heights of trees on- and off- landing areas become more pronounced with time. For example, Carr (1987a) found that on-landing trees were 54% and 77% of the height of off-landing trees after six years of growth, for winter and summer landings, respectively. After 11 years of growth, height comparisons were even more dramatic. On-landing trees were only 38% and 42% of the height attained by off-landing trees, for winter and summer landings, respectively. For the 30 year-old skid roads studied by Wert and Thomas (1981), the stand volume of skid roads was 74% lower than that of off-trail areas.

During the construction of landings, forest floor are removed while the topsoil layers may be removed or mixed with the subsoil (Kranabetter and Osberg 1995). Regardless of which construction method is used, the result is a compacted soil with poor water permeability, from which the nutrients crucial to plant growth have been stripped away, where the soil organisms responsible for nutrient cycling are absent, and where the organic matter key to the survival of soil organisms has been removed (Carr 1987a, Miller et al. 1996, Bulmer 1998).

A broad range of methods are being tested for their success in improving the soil condition of landings. These techniques range from tillage with or without seeding fallow crops or fertilization to respreading topsoil in combination with tillage and organic matter amendments such as pulp mill and municipal sewage wastes (biosolids)[1] and chipped slash. Addition of organic matter or establishment of grasses and legumes following tillage maintains soil nutrient status and nutrient cycling over the long term, provides organic matter, and prevents soil erosion (Carr 1987a, Kranabetter and Osberg 1995, Dick et al. 1988, Harris et al. 1993).

Many projects have been initiated using a variety of techniques (such as tillage, fertilization, and seeding of fallow crops) in an attempt to rehabilitate landing areas. Although results have been promising, none of the landing reclamation trials have been able to restore the sites to their previous productivity levels (e.g., Carr 1987b, Arnott et al. 1988) and many (such as Kranabetter 1990 and Kranabetter and Osberg 1995) had problems with the timing and consistency of treatment application. Even when improvements in bulk density and soil nutrient status were evident, they did not always result in significant changes in foliar nutrient status. Reasons for this have not yet been identified. Studies which find measurable improvement in soil nutrient status over the short-term still often express pessimism

[1] Solid material removed from domestic or industrial waste water and treated with various degrees of digestion and/or composting (Brady and Weil 1999, pp. 534-535).

regarding long-term nutrient status (Kranabetter and Osberg 1995, Carr 1987b, Arnott et al. 1988).

Successful techniques for application of biosolids in landing reclamation have not yet been fully established. The benefits of biosolid application in landing reclamation for tree growth are not entirely known, and there is little documentation of landing reclamation trials involving biosolids. However, some research has been done using biosolids as fertilizer for forest soils (Jackson et al. 2000, Labrecque et al. 1998, Harrison et al. 1996, Medalie et al. 1994). Improvement in tree height growth from biosolid application ranged from 2% for young trees on a site class II stand to 72% for young trees on a site class IV stand, both in Washington, USA (Henry et al. 1993). In a study by Moffat and Mathews (1991), significant growth increases were also found following application of liquid-digested sewage sludge to a 32 year-old forest on nutrient-poor, coarse-textured soil. This study found no increases in foliar nutrient levels of heavy metals, with the exception of lead which was also found in above-normal concentrations in the litter and soil of the site. Some researchers (Hue et al. 1988, Labrecque et al. 1998) also found no correlation between foliar metal accumulation and concentrations of metals in applied sludges, while others have found a correlation (Brockway 1983).

The purpose of this thesis is to determine the effectiveness of biosolid application in improving soil conditions and seedling growth on forest landings. The information provided in the thesis is based on a study (1998-2000) conducted in the Sub-Boreal Spruce (SBS) biogeoclimactic zone, British Columbia (BC). The objectives of the study were to examine the effects of biosolids with or without fallow legumes and grasses on: (1) soil physical and chemical properties; and (2) seedling growth. This thesis will provide some documentation on whether landing tillage was successful in this reclamation trial, it will add to the available knowledge on how effective organic matter amendments are in landing reclamation, it will provide information from control areas on soil properties and foliar nutrient status, and it will enhance the local confidence in reclamation using locally available organic matter amendments.

Chapter II – Literature Review

2.1 Impact of forest landings on soil properties

Forest landings are areas where timber is collected for removal from a cut block. During landing construction, the first two layers of soil (A and B horizons) and the forest floor may either be removed during full-bench landing construction, or mixed with the subsoil (C horizon) in partial-bench landing. Detrimental impacts of landings on the soil are a result of the construction and use of the landing. The changes in physical, chemical, and biological properties of soils used for landings are associated with soil compaction and removal of forest floor (Carr 1987a, Miller et al. 1996).

Although machine traffic causes soil compaction and increases in soil bulk density[2], subsoils exposed during the construction of landings are naturally more dense than topsoil (Carr 1987a). The degree to which machine traffic and the higher bulk density of subsoils contribute to observed increases in soil bulk density depends on the season, soil type, and the soil moisture level during landing construction and use (Carr 1987a, Carr 1988). For example, winter landings do not to undergo as much compaction as summer landings. This has been attributed to both the protection provided by snow and to frozen ground having a greater resistance to compaction (Carr 1987a). Wet and fine-textured soils are generally more susceptible to compaction than dry and high sand content soils (Howard et al. 1981).

[2] "Bulk density is the mass per unit volume of oven dry soil, calculated as follows: bulk density = $\frac{\text{mass oven dry}}{\text{volume}}$ (Foth 1990, p.33)."

Soil compaction reduces soil macropore structure (Carr 1987a) as larger flow channels are reduced to smaller flow channels, or as soil aggregates change their orientation (Lenhard 1986). These changes in macropore structure lead to decreases in soil permeability, hydraulic conductivity, and diffusion rates of gases (Carr 1987a, Lenhard 1986, Miller et al. 1996, McNabb 1994, Bulmer 1998, Hatchell et al. 1970, Nambiar and Sands 1992).

Removal of forest floor is associated with losses of nutrients from the ecosystem, destruction of habitat for soil flora and fauna, disruption of nutrient cycling, loss of soil temperature regulation, alteration of soil structure, increased soil strength, reduction in effective rooting depth, and accelerated soil erosion (Carr 1987a, Lenhard 1986, Bulmer 1998, Prichette and Fisher 1987). Further effects on the forest soil which are less widely discussed than those associated with compaction and forest floor removal include the mixing and inversion of soil horizons, puddling, and the displacement of soil which results in a mosaic of soil thickness and exposed soil horizons (Miller et al. 1996, Bulmer 1998). From the perspective of forest productivity, the most important factors on this list of consequences are those which are predominant in producing an unfavorable rooting environment for seedlings: increased soil strength, poor soil aeration, and nutrient depletion (Carr 1987a). For developing trees, these changes affect, "...seedling establishment, development, and growth rate," (Carr 1987a, p. 3).

Increases in bulk density from forest harvesting activities persist in the soil for considerable periods of time. Wert and Thomas (1981) found that soils of skid roads approximately 30 years old still had elevated bulk densities in the 20-30 cm soil stratum, while soils at a depth of 0-15cm had largely recovered from compaction. The authors concluded that the remaining increases in bulk density would persist throughout the rotation.

2.2 Effect of soil compaction on coniferous seedling growth and foliar nutrient status

A limit of 1300-1400kg/m^3 is given as the maximum bulk density that can be tolerated by many tree species (Carr 1987a). Bulk densities above this limit are frequent on forest landings, but can occasionally be found in undisturbed soils in BC (Arnott et al. 1988, Sanborn and Bulmer 1996). Reduced tree growth on landings may be a reflection of: "1) increased resistance to root growth, 2) poor soil aeration resulting from loss of pore structure, 3) limited nutrient availability following displacement of the forest floor and top soil in combination with causes (1) and (2), and 4) restricted activity of soil micro- and macro-organisms (Carr 1987b, p. 1);" (Kranabetter and Osberg 1995, Balisky 1995). Dramatic reductions in tree growth have been observed at some sites while others experience insignificant reductions in growth. These variations are likely due to the same site-specific variables which govern the degree of compaction that results from landing construction and to the tolerance of the species of tree planted to those conditions (Carr 1987a, Howard et al. 1981).

Observations covering long periods of time frequently report that differences between height of trees on- and off-landing areas become more severe as time passes. For example, in his study of winter and summer landings, Carr (1987a) found that on-landing, trees were 54% and 72% of the height of off-landing trees after 6 years of growth, for winter and summer landings, respectively. After 11 years of growth, height comparisons were even more disparaging; on-landing trees were only 38% and 42% of the height attained by off-landing trees (winter and summer landings, respectively). On another study site, on-landing trees were all significantly smaller than their off-landing counter parts after just three years of growth (Carr 1988). In each subsequent year, the gap between the total heights of the off- and on-landing trees continued to increase (Carr 1988). For the 30 year-old skid roads on loamy soils studied by Wert and Thomas (1981), the stand volume of skid roads was 74% lower than that of off-trail areas. The skid trails also had 41% fewer trees than areas which had not experienced severe soil disturbance.

Under some conditions, however, tree growth may not be impaired. If air, water, and nutrient supplies are favorable, then a restricted root zone or low soil nutrient status may not be reflected by poor tree growth (Carr, 1987a). For example, Miller et al. (1996) found that there were no significant differences in height growth between sites with ripped and unripped skid trails in coastal Washington with burned and unburned slash, even though bulk density had been increased by 40% or greater compared to non-skid trial areas in the cut blocks. However, the maximum bulk densities achieved following skid trail construction was 1160kg/m^3, which is a bulk density well below many of the maximum bulk density limits for tree growth reported in the literature surveyed by Miller et al. (1996). The researchers concluded that the favorable climate of the site and its nutrient status were sufficient for the seedlings to overcome barriers presented by the increased bulk density of the soil.

Impacts on foliar nutrient status are also variable. In a study by Carr (1987a) of landings used in the winter and in the summer in the Prince George Forest District, six year-old seedlings on- and off- landing areas had similar foliar nutrient levels of nitrogen, phosphorous, and potassium. Eleven year-old trees, on the other hand, had levels of foliar nitrogen below acceptable limits for lodgepole pine. Carr (1987a) concluded that the nitrogen deficiency was due to a depletion of nutrients available in the restricted rooting zone of the trees. In another study conducted in the Fort St. James area of BC, Carr (1988) found that needles of trees growing on landings for 6 years had adequate foliar nitrogen while 8 year-old trees were found to reflect a severe nitrogen deficiency and he suggested that phosphorus would also become deficient over time due to the small amounts of phosphorous left on-landing. Since seedlings which were 6 years old did not reflect nutrient depletions in foliar nutrient levels and those which were 8 and 11 years old did show such depletions, it is possible that short-term studies reflecting sufficient initial foliar nutrient levels may not necessarily reflect sufficient long-term nutrient prospects.

2.3 Principles, difficulties, and opportunities of reclaiming compacted soil

A researcher attempting to rehabilitate degraded forest soil for improved long-term site productivity must deal with two issues: 1) soil decompaction to improve soil aeration; and 2) enhanced growth of soil organisms to improve nutrient cycling. Implicit in these directives is the creation of good soil structure, either by returning topsoil reserved for replacement onto disturbed areas, or by innovative means of replicating a functioning soil ecosystem. To this end, a broad range of methods have been tested for their success in improving the soil condition of landings. These techniques range from tillage with or without seeding of fallow crops or fertilization, to more involved measures combining tillage with various forms of organic matter amendment such as biosolids, respread topsoil, and chipped slash.

The conclusion made from anecdotal information from foresters involved in reclamation of landings is that tillage and seeding with grasses and legumes and/or fertilizing are effective treatments for restoration of landings on sandy soils to their original site class of forest productivity (Sanborn, pers. comm. 1997; Revel 1994; Bulmer 1997; Bulmer, pers. comm. 1998). Methods for the reclamation of fine- and medium- textured soils are still in an experimental stage. These soils will often reconsolidate in less than a year after tillage. Following recompaction, bulk densities can be higher than before tillage; a problem that can be most prevalent on, but not restricted to, fine-textured soils (Lousier, pers. comm. 1997; Kranabetter and Osberg 1995; Sanborn and Bulmer 1996; Bulmer, pers. comm. 1998).

Application of biosolids to landings provides organic matter which stabilizes decompacted soil and provides a growth medium for soil organisms. The use of pulp sludge has been regarded as beneficial because it prevents this material from being discarded in landfill or disposed of by incineration, or by discharge to surface waters, and thereby avoids the expense of these methods of disposal (Swan et al. 1997, Cabral et al. 1988, Moffat et al. 1991). Biosolids are readily available and they can act as an organic fertilizer. However, the level of nutrient contribution by biosolids depends on the qualities of the biosolid used (Van Ham, pers. comm. 1997; Cabral et al. 1998). Indeed, some biosolids have low nutrient content and other chemicals unfavorable to tree growth, and could therefore reduce rather than assist tree growth (Kranabetter 1990, Cabral et al. 1998). This has caused some reluctance to use pulp and municipal sludges as an amendment. However, addition of fertilizer to the biosolid or combining biosolids for optimum nutrient release compensates for problems with low or excessive nutrient levels (Kranabetter 1990, Jackson et al. 1999).

Another issue confounding studies of land applications of sludges is the variability of the characteristics of sludge. Properties of the sludge change from year to year, or season to season, as a result of variations in the properties of the raw materials, levels of biological activity, and operational changes in the facility (Cabral et al. 1998, Schnaak et al. 1997). Stockpiling can also change the characteristics of sludge; a gradient from the exterior to the interior of the pile will form over time and cause variations in measurements taken from a single amendment (Cabral et al. 1998, Harris et al. 1993). These problems are minor, however, compared to the opportunity of using biosolids to enhance soil fertility and at the same time find alternatives to landfilling.

There is also some concern with land application of biosolids causing large N additions that result in nitrate leaching to groundwater, and with the addition of very high levels of heavy metals or organochlorines (Cabral et al. 1998, Brockway 1983). However, when application rates are kept within governmental guidelines phytotoxicity, toxicological problems for wildlife, and leaching of heavy metals and excess nutrients to groundwater do not occur (i.e. Labrecque et al. 1998, Cabral et al. 1998, Catricala et al. 1996, Medalie et al. 1994, Jackson et al. 2000).

In order to increase public and professional confidence in the safety and utility of biosolid applications, it is essential that local trials using locally available amendments are conducted, evaluated, and publicized. Alternative waste management and forest improvement can enhance each other and it is the intention of this thesis to facilitate local confidence in the use of biosolids in forestry reclamation as well as take the problems of waste product disposal and forest decline and turn them into mutual solutions.

2.4 Responses of landing soils and seedling growth to reclamation trials

Most studies on landing reclamation have used tillage as the primary means of reclamation. Tillage of compacted soils has had variable levels of success in alleviating soil compaction and improving tree growth. This variability has been attributed to soil type, the moisture content of the soil at the time of ripping, and the treatments the landing receives after ripping. For example, Kranabetter and Osberg (1995) fertilized and tilled landings on different soil types and then applied combinations of topsoil respreading and seeding legumes. Improvement in bulk density was greatest where topsoil had been respread (whether on fine- or coarse- textured soils) or where the soil was sufficiently coarse-textured to not recompact after tillage. Data collected by Revel (1994) from trials involving tillage of 68 landings illustrated the reduction in tree leader length and height growth that can occur as a consequence of recompaction.

Recompaction occurs because tillage cannot replicate the stability of soil aggregates which form over time as a result of plant growth and biological activity (Kranabetter and Osberg

1995, Juma 1994). Landing reclamation using addition of organic matter or establishment of grasses and legumes following tillage hopefully will prevent recompaction and improve soil condition (Kranabetter and Osberg 1995, Sanborn and Bulmer 1996). These treatments may also add soil nutrients, provide organic matter content, and prevent soil erosion (Cabral et al. 1998, Carr 1987a, Kranabetter and Osberg 1995)

Trials evaluating the success of road decommissioning are more numerous than landing reclamation trials, however it is not certain whether results of these studies can be extended to landing reclamation. In a study which included reclaiming a skid road and a landing area, Carr (1987b) found that ripping, establishment of fallow crops, and moderate soil nutrient levels, enhanced the annual growth increment of seedlings planted on treated road sections to five times that of seedlings grown on untreated road sections. After seven years, the total growth of seedlings on treated sections was three times greater than that of seedlings grown on untreated sections. However, these same treatments on landing areas produced no improvement in height of seedlings growing on treated landings over seedlings growing on untreated landings. The study's landing area trials were only two years old, however, and Carr (1987b) stipulated that as seedling nutrient requirement increased, there may be a response to the higher nutrient levels provided by the green fallow and some improvement in soil bulk density cause by root growth of the fallow crop. At the time of his study, the foliar nutrient status of the seedlings on the landings was found to be adequate.

Researchers have yet to ascertain the fundamental techniques for landing reclamation. For example, Bulmer (1998) states that more studies need to be conducted in order to fully establish the details of how tillage of landing areas should be conducted in BC. Of those studies which can be obtained, many did not take tree growth or soil bulk density data from a control area, nor do they provide pre-treatment site description. Without pre-treatment site description or information from a control area, inference cannot be made about how successful landing reclamation treatments were in restoring site productivity. Even rarer are studies including information on how reclamation has affected foliar nutrient status.

2.5 Responses of nutrient-depleted forest soils to organic matter amendments

It is now recognized that, in order to maintain an acceptable long-term soil nutrient status, reclamation projects must address issues of lack of organic matter and microbial biomass (Dick et al. 1988, Harris et al. 1993). Soil nutrient cycling is dependent on these two features of the soil environment, and therefore, so is tree growth (Foth 1990, Kranabetter and Osberg 1995). Addition of organic amendments, such as primary pulp-mill sludge, to soil promotes soil aggregate stability, increases water-holding capacity, porosity, organic matter content, soil aeration, and improves bulk density (Cabral et al. 1998). Other organic matter amendments like municipal biosolids, fly ash, and agricultural waste product slurries are also sources of nutrients and organic carbon (Henry et al. 1993, Xiao et al. 1999, Jackson et al. 1999), and with increasing the pH of acidified soils (Catricala et al. 1996, Cabral et al. 1998).

Presumably because of their lower nutrient status, many forest fertilization have been conducted using coarse-textured soils (i.e., Medalie et al. 1994, Jackson et al. 2000, Harrison et al. 1996). In these soils, biosolid amendment has been able to decrease the C:N and increase the amount of total and exchangeable P, K, Ca, and Mg (Harrison et al. 1994). A decrease in pH is typically seen following biosolid application as a result of nitrification, nitrate leaching, and the associated companion leaching of cations from the soil profile (Harrison et al. 1994, Moffat et al. 1991). It remains to be seen whether this acidity will be responsible for stripping the soil of cations to a level even lower than that previous to amendment.

Field trials with locally available organic matter will provide information for moving towards the establishment of recommended use guidelines for organic matter amendment in landing reclamation. It will also help develop local proficiency in application techniques, which will in turn decrease the costs of reclamation.

2.6 Changes in conifer foliar nutrient status and growth as a result of organic matter amendments in forestry reclamation and fertilization trials

There is little documentation of landing reclamation trials involving biosolids and other organic matter amendments. However, much research has been done using biosolids as fertilizer for forest soils. Increases in the foliar concentrations of a given element as a result of organic matter amendment depend on the amount of element applied, the form of the element (i.e. labile or recalcitrant), tree species, and an interaction of the characteristics of the organic matter amendment(s) and the soil to which it is applied which cause the element to be mobilized or made to be made unavailable (i.e., Prescott and Brown 1998, Jackson et al. 1999, Kraske and Fernandez 1993, Xiao et al. 1999). The degree of benefit from organic matter amendment in plant growth depends on adequacy of plant nutrition prior to biosolid application, and on interactions of organic matter amendment(s) with the soil which mobilize or fix plant nutrients (i.e., Hue et al. 1988).

A variety of organic amendments have been found to produce improvements in growth of pine species. Improvement in tree height growth for young trees from biosolid application ranged from 2% on a site class II stand to 72% on a site class IV stand, both in Washington, USA (Henry et al. 1993). Moffat et al. (1991) also observed significant growth increases following application of liquid-digested biosolids to a 32 year-old forest on nutrient-poor, coarse-textured soil. Increased needle length, fasicle dry weight, and radial growth at breast height have been attributed to the organic fertilization trials (Brockway et al. 1983, Moffat et al. 1991).

There are cases, however, where organic matter amendments have not improved tree growth. Pulpmill wood waste (knots, clairifier sludge, and grit) was tilled into landings planted with black spruce seedlings in New Brunswick (West and Bishop 1987). The authors concluded that the poor growth and colour of the seedlings at the end of the first growing season was a result of the high carbon to nitrogen ratio (C:N) of the amended soil rather than low nutrient levels. Cases such as this represent a need for further refinement of technique rather than an absolute failure of organic matter amendments to enhance tree growth.

For reasons mentioned above, there is not always a direct correlation between foliar concentration of an element and the amount of sludge applied to an area. On 36 to 40 year-old red and white pine plantations with sandy soils, Brockway et al. (1983) applied two organic amendments (an ammonia and phosphoric acid enriched papermill biosolid, and a municipal biosolid). Both amendments increased foliar N compared to controls. Fourteen months after treatment application, unfertilized areas had a range of Kjeldahl N of 1.09 to 1.30% while those with 32 Mg/ha papermill biosolid or 19.3 Mg/ha municipal biosolid had 1.36 to 5.03% Kjeldahl N. Other nutrients in foliar samples were unaffected by the fertilization. Rate of heavy metal concentrations in biosolids is also uncorrelated with foliar metal accumulation (Moffat et al. 1991, Brockway et al. 1983). Moffat et al. (1991) found no increases in foliar levels of heavy metals as a result of liquid-digest biosolids, with the exception of lead which was also found in above-normal concentrations in the litter and soil of the site.

Unfortunately, a broad spectrum of published data from trials done in British Columbia or with lodgepole pine *(Pinus contorta* Dougl. *ex* Loud.*)* is not available on the subject of foliar nutrient status. This is not because researchers have omitted sampling for foliar nutrient status but is more a symptom of the fact that so few studies are available of forestry fertilization or reclamation trials.

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Chapter III -

Comparison of soil properties on landing areas reclaimed with tillage, biosolid amendment, and seeding of a fallow crop

Abstract

Soil compaction following tillage of forestry landings on fine- and medium-textured soils may be alleviated by addition of organic matter. This study was an evaluation of the impacts on soil properties of the reclamation of a compacted Gleyed Eluviated Dystric Brunisol. The reclamation techniques included tillage, addition of a mixture of land stored primary clarifier waste and municipal biosolids to the soil, and seeding fallow legumes and grasses. Application rates were 70 Mg/ha of municipal biosolids and 155 Mg/ha of clarifier waste. Soil properties including bulk density, %C, pH, available NO_3-N and NH_4-N, C:N, base saturation and ECEC (displacement by $BaCl_2$ method), and total elemental composition (by mixed acid microwave digestion) were compared between plots treated with tillage and biosolid (with or without seeding), tillage only treated plots (with or without seeding), and control plots. Statistical analysis (restricted complete randomized block) of pH_{CaCl2}, ECEC, C:N, and total Na, Ca, P, and K found significant differences for all main effects and interactions within each depth; however, only reclamation treatments were subjected to planned and post-hoc comparisons. The pH, ECEC, total P, and total Ca of landings where biosolids were applied were significantly higher than tillage-treated and control plots. In comparison to plots treated with tillage only or control plots, landings where biosolids were applied after tillage had significantly lower C:N and total Na. Pair-wise comparisons of treatments within each depth for total K were generally non-significant. Comparison of descriptive statistics of tillage-treated plots to biosolid-treated plots suggested that biosolid application decreased soil bulk density. Seeding had no significant effect on soil properties.

3.1 Introduction

Construction and use of forest landings creates changes soil properties that are unfavorable for plant growth and microbial activity (Bulmer 1997, Dick et al. 1988). These changes include increased bulk density and reductions in macropore structure, nutrient pools, water permeability, hydraulic conductivity, and gas diffusion rates (Carr 1987a, Lenhard 1986, Hatchell et al. 1970). Successful reclamation of landings on coarse-textured soil has been achieved with decompacting the landing by tillage or ripping, and fertilization or planting of legumes (Bulmer 1997). However, we are not yet knowledgeable enough regarding what depth of decompaction is required for successful reclamation, nor regarding the most effective methods of decompaction (Bulmer 1997). Reclamation of landings on fine- and medium-textured soils tends to be more problematic because these soils have a greater tendency to recompact (Lousier pers. comm. 1997, Kranabetter and Osberg 1995, Sanborn and Bulmer 1996). There is the possibility that landings on medium and fine-textured soils can be reclaimed by adding carbon- or nutrient- rich wastes from a variety of industries. The incorporation of such wastes with soil in a decompacted landing area has the potential to provide a substrate for microbial activity, a more favourable rooting environment for plants, a source of nutrients for plants and microbes, and a medium which could prevent the recompaction of fine- and medium- textured soils (Kranabetter and Osberg 1995, Sanborn and Bulmer 1996).

Unfortunately, studies using biosolid amendments in landing reclamation are generally limited in the literature. Published and unpublished studies which are available show that landing reclamation using biosolids, respreading stockpiled topsoil, chipped slash, and other amendments with high C:N (carbon to nitrogen ratio) have often been hampered by addition of too much organic carbon. Kranabetter (1990) found that microbial activity may have been impaired in his study sites because the pulp mill biosolids had been mixed too deeply into the soil. Similarly, Kranabetter and Osberg (1995) were unable to obtain consistent results using topsoil respreading due to inadvertent addition of slash during the mixing of the topsoil with the landing bed. Conclusions from both papers stipulated that large size of pulp sludge aggregates and addition of 'extra' from slash may have acted to sequester nutrients rather than restoring nutrient cycling.

Data from control plots provides reference information to assess the effects, if any, of using organic matter amendments in landing reclamation. In order to have reference data to compare with treatment results, the present study includes an untreated landing area and an off-landing control area. The objective of this study is to assess the efficacy of tillage, biosolid application, and seeding fallow legumes and grasses in ameliorating the soil condition of two landings constructed on medium-textured soil. The following variables were measured in order to asses this experiment: bulk density, pH, exchangeable cations, cation exchange capacity, base saturation, and C:N.

3.2 Materials and methods

3.2.1 Study area

Two landings were used as the study plots for this study, and they were located approximately 30 km south-west of Prince George at roughly N 53° 39' 13", W 122° 56' 49" using datum NAD 83 (Figure 3.1). The soil of the landings was a loam (52% sand, 38% silt, and 10% clay) and the landings were 0.2 and 0.3 ha (Figure 3.2). Access to the area was well maintained as the landings were located off a logging road originating at the 1.5 km mark of the Pelican Forest Service Road, which branches off from Blackwater Road. This region is within the Sub-Boreal Spruce (SBS) biogeoclimactic zone and the soil in the cut block surrounding the landing was a Gleyed Eluviated Dystric Brunisol.

Table 3.1 shows results of soil analysis of pre-treatment samples taken in August of 1998. Statistical analysis of the results of the pre-treatment soil analysis was not conducted as this information was gathered for site description. Soil profile descriptions were done in the cut block surrounding the landings (Tables 3.2 and 3.3).

3.2.2 Selection of organic matter amendments

Use of pulp mill or municipal biosolids alone was not appropriate for the reclamation objectives of this study. Primary pulp mill sludge alone cannot return a site's productivity because it has a high C:N and is not a good source of plant nutrients (Catricala et al. 1996). Municipal biosolids alone are too labile to provide a source of stable organic matter for re-establishment of soil physical properties. Optimal levels of pulp mill and municipal biosolids to be applied to the study area were determined by Van Ham (1998) based on the pre-treatment soil conditions, the decomposition rates of pulp mill and municipal biosolids, loss of organic matter as a result of decomposition, the potential for nutrient leaching, and a target C:N of 15 in the amended soil.[3] This was accomplished by combining Prince George municipal biosolids and land stored primary clarifier waste from the Prince George Pulp and Paper Mill owned by the Canadian Forest Products company, at a dry-weight ratio of 1:2.2 and an application rate (in dry weight) of approximately 70 Mg/ha of municipal biosolids and 155 Mg/ha of clarifier waste (Van Ham 1998). These application rates were approved by the Ministry of Environment, Lands and Parks under Permit #146 of the City of Prince George (Van Ham 1998). Selected results of chemical analysis commissioned by Van Ham (1998) on the biosolids is presented in Table 3.4.

3.2.3 Application of treatments

In August of 1998, the landings were tilled by an excavator to a minimum depth of 30 cm. Following tillage, two portions of each landing were designated as tillage treatment only plots where samples could be taken to demonstrate differences between amended and unamended soil properties. On the main portion of the two landings, land stored primary clarifier sludge and municipal biosolids were mixed on-site by the excavator. This mixing was done by dropping scoops of each material onto approximately 2 m^2 of tilled landing and lifting the amendments with the soil, dropping it back on the 2 m^2 and raking the surface to flatten out

[3] A C:N of 15 is considered an indicator of good soil biological, chemical, and physical properties (Van Ham 1998, Catricala et al. 1996).

the mound. Biosolids were thus incorporated through out the depth of the pre-tilled soil, however biosolid addition was greater in the upper layers of the tilled soil than in the lower portions of the pre-tilled soil. The excavator operator was very conscientious and mixing of biosolids with soil was very even: there were no 'pockets' on the landing which had a high content of either type of biosolid.

As mentioned above, portions of the landing were tilled but not given organic matter amendments. One of these tilled plots was seeded with fallow legumes and grasses (seeding plus tillage or "S+T' treatment). The other tilled portions was not seeded (tillage or "T" treatment). Biosolid-treated plots were also divided into unseeded ("B") and seeded plots ("B+S"). Figure 3.2 shows the location of these treatment plots on each landing.

The seeding mixture, Rapid Grow Revegetation Mixture (Richardson Seed), had been used for other reclamation trials by Van Ham (pers. comm. 1998). Plant species in the seeding mix were as follows (percentages are by weight):

50% fall rye
15% perennial ryegrass
10% creeping red fescue
10% timothy
5% Italian ryegrass
5% red clover
5% white clover

The rye and ryegrass in the mixture were not expected to reach reproductive maturity before the end of the growing season. Seeding was done at a rate of 112 kg/ha and occurred immediately following biosolid treatment application in the week of August 16th, 1998. For tillage-treated areas, seeding was done 2 days after tillage.

While it is unfortunate that only two landings were included in this study, there were logistical limitations preventing the inclusion of more landings. First of all, an unlimited budget for excavator operation time was not possible. Second, these were the only two landings sufficiently close together to permit assumptions of similar soil types and similar landing use and age. Reclaiming additional landings in 1999 was considered, however comparison between landings reclaimed in different years would have been confounded by variation in sludge composition (Cabral et al. 1998) and annual climatic variation.

3.2.4 Timing of sampling and study design

Soil sampling was conducted over a two year period, in addition to the assessment of pre-treatment conditions prior to plot establishment in the Fall of 1998. Post-treatment soil samples were taken at the peak of the growing season (late June to early July in 1999 and the last week of July in 2000).

Three sampling locations for soil sampling were selected randomly in each treatment plot before treatment application in August of 1998. Soil was sampled from these pre-selected plots before treatment application in 1998 and after treatment in 1999 and 2000 at three depths: 0-10 cm[4], 10-20 cm, and 20-30 cm. Thus, a total of 72 soil samples were collected in each year (4 experimental plots x 3 sampling locations x 3 depths x 2 landings = 72 experimental samples).

During soil sampling in the spring of 1999 and 2000, three sampling locations were also selected randomly on a plot in the cutblock (off-landing plot "OL") and a portion of untilled and unamended landing (control plot or "CP"). These samples serve as the basis for evaluating the success of the reclamation trial (3 samples x 2 comparison plots x 3 depths = 18 comparison samples).

The formulae below summarize the design of this project.

2 landings (2 levels of biosolid x 2 levels of fallow crop)
= 8 experimental plots

1 untreated control + 1 off-landing reference
= 2 control plots

For an overall design of:
(2 landings x 4 experimental plots per landing) + 2 control plots
= 10 total study plots in a 2x2x2 design (2 levels of biosolids, 2 levels of fallow crop, 2 levels of tillage)

The following is a summary of the plot treatment acronyms used frequently throughout this thesis:

L1 = Landing 1
L2 = Landing 2
B+S = biosolid + seeding treatment plots
B = biosolid only treatment plots
S+T = seeding + tillage treatment plots
T = tillage-only treatment plots
OL = off-landing cut block plot
CP = control plot (landing with no reclamation treatment)

[4] There was no litter layer present, hence the surface of the landing or of the treated soil is represented by the 0 cm value.

study plots = all of the above plots (B+S, B, S+T, T, OL, and CP)
experimental plots = all those plots which received a reclamation treatment (B+S, B, S+T, and T)
biosolid-treated plots = B+S and B
tillage-treated plots = S+T and T
reference plots = the two plots which were not manipulated (OL and CP)

3.2.5 Soil analysis

3.2.5.1 Sample processing and bulk density measurement

A number of alterations to the traditional procedures for soil sample processing and bulk density measurement had to be made in this study. Normally, bulk density samples are dried at 105°C for 48 h and samples for chemical analysis are air-dried (Blake and Hartge 1986, Kalra and Maynard 1991). In this study, the samples being used for bulk density were also to be used for chemical analysis because of the difficulty of collecting samples from compacted soil. Concern that oven-drying would cause excessive changes in soil properties caused the selection of a slightly lower temperature (95°C) at which to dry the soils, as it was deemed more important to avoid the introduction of artifacts in chemical analysis than to obtain bulk density measures in perfect accordance with traditional methods. However, weight of sub-samples dried at 95°C and 105°C for 48h were not significantly different ($p > 0.05$, data not presented), therefore it is not anticipated that bulk densities reported herein are significantly inflated by excess moisture.

Soils of the study area contained approximately 10 to 40% coarse fragments depending on depth, hence use of a thin-walled metal cylinder 7.5 to 10 cm in diameter, as per the traditional method of obtaining bulk density samples, was not appropriate (Blake and Hartge 1986). Instead, a large soil corer (15cm diameter) was used to take soil cores at depths of 0-10 cm, 10-20 cm, and 20-30 cm. The samples were put in plastic bags, labeled, transported back to the laboratory, and placed in drying ovens at 95 °C for 48 h. Samples were not weighed before drying because this information was not necessary for the assessment of the success of landing reclamation treatment. After being oven-dried, samples were weighed and then sifted through a 2 mm mesh. As the samples were being sifted, coarse fragments were reserved. These coarse fragments were weighed and their volume was determined by the volume of water they displaced. These values for coarse fragment mass and volume were subtracted from the soil bulk density measurement in order to produce a more accurate estimate of soil bulk density. Large overestimates of soil bulk density were caused by the very high mass and relatively low volume of the stones (data not presented), hence it was necessary to correct for the mass and volume of the coarse fragments.

As summarized in 3.2.4, there are ten sample plots in this study, each with three sampling locations and three depths (0-10 cm, 10-20 cm, and 20-30 cm) per sampling location. This gives a total of 90 soil samples taken in 1999 and 2000. Pre-treatment samples were taken on-landing only, therefore 70 soil samples were taken in 1998.

3.2.5.2 pH

Both distilled deionized water and 0.01 *M* $CaCl_2$ were used as suspension media for obtaining pH of the soil samples (pH_{H20} and pH_{CaCl2}, respectively). This was done in order to be able to compare results of this study with other studies, regardless of the method of pH determination used. A soil-to-solution ratio of 1:2 was used for all samples except biosolid-amended samples from the 0-10 cm layer. For these amended 0-10 cm layer samples, a 1:4 ratio was employed (Kalra and Maynard 1991). Approximately half of the samples where a 1:4 ratio was used were double-checked with a 1:2 ratio. Results from either soil-to-solution ratio were nearly identical (a subjective comparison, not statistically analyzed).

For both suspension media, 20 ml of solution were added to 10 g of sieved soil in a 50 ml Nalgene centrifuge tube. The solution was allowed to absorb into the soil without stirring (Kalra and Maynard 1991), and then the tubes were capped and placed on a reciprocating shaker for 30 minutes. After agitation, the samples were let to settle for a further 30 minutes and then pH was measured by using a Canlab Model 607 pH meter calibrated with pH 4.0 and 7.0 buffers (Kalra and Maynard 1991).

3.2.5.3 Effective Cation Exchange Capacity (ECEC), Exchangeable Cations, and Base Saturation

Effective cation exchange capacity (ECEC) and exchangeable cations were evaluated using displacement by 0.1 *M* $BaCl_2$ summation method (Hendershot et al. 1993). This was done by adding 30 ml of 0.1 *M* $BaCl_2$ to 20 g of soil in 50 ml centrifuge tubes and shaking for 2 h using a reciprocating shaker. The suspensions were allowed to settle overnight in a refrigerator and the supernatant was drawn for Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) analysis of exchangeable Ca, Mg, K, Na, Al, Fe, and Mn. ECEC and base saturation (BS) were calculated as per Hendershot et al. (1993):

$$ECEC = \sum M^+ \ cmol_+/kg \qquad \text{where } M^+ = Ca, Mg, K, Na, Al, Fe, Mn$$

$$BS = \frac{\sum M^+ \ cmol_+/kg}{ECEC} \times 100 \qquad \text{where } M^+ = Ca, Mg, K, Na$$

3.2.5.4 Total Carbon and Total Nitrogen (%C and %N)

Ten gram subsamples of the 90 sieved soil samples taken annually were individually ground to approximately 150 µm using mortar and pestle. The ground subsamples were analyzed by a Fisons Instruments elemental analyzer (Na 1500 NC) for total C (%C) and total N (%N). A thermoconductivity detector (TCD) in the elemental analyzer evaluates the amount of C and N present when samples are ignited at 900 to 1050 °C. Peaks generated by the TCD are converted to %C and %N by sample mass (Essler, pers. comm. 2002). C:N for each sample was calculated from these results.

3.2.5.5 Available nitrogen

Ammonium (NH_4-N) and nitrate (NO_3-N) were extracted with 2 *M* KCl by the High Volume Lab at the University of Alberta. Individual 10 g subsamples of the 90 sieved soil samples taken annually were shaken for 30 min on a reciprocating shaker with 50 mL 2 *M* KCl. Following shaking, the samples were filtered and analysed by a Technicron Autoanalyser II, 1973, within 24 h (Maynard and Kalra 1993).

3.2.5.6 Total elemental analysis

The total amount of the elements of interest present in the soil was investigated using microwave mixed acid digestion. The method of microwave mixed acid digestion used is the standard procedure of the Central Equipment Laboratory of the University of Northern British Columbia. Approximately 0.2 g of each of the soil samples taken annually and ground to approximately 150 μm using mortar and pestle (see section 3.2.5.4) was placed individually in Teflon 'bombs' and H_2O_2, HCl, HNO_3, and HF were added to the soil. Reagent amounts and concentrations that were used in microwave acid digestion of soil samples are listed in Table 3.5. The bombs were placed in a digestion block and microwaved in a Milestone Laboratory Systems microwave (Mls 2000 mega), for approximately 30 min; times and watts for the microwave program can be found in Table 3.6. Following microwave digestion, 4.5 g boric acid and 30 ml nanopure H_2O were added to the bombs and microwaved again using the same program. Lastly, the digested samples were transferred to a 50 ml volumetric flask and nanopure H_2O was added till the total volume was 50 ml. The samples were then stored in Nalgene containers and sent for analysis of Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, and Zn by ICP-AES.

3.2.6 Statistical analysis

This study had a restricted complete randomized block design with unequal sample sizes. The list of dependent variables available for statistical analysis outstriped the guideline of having a sample size equal to or greater than the number of dependent variables (Tabachnick and Fidell 2001), hence it was necessary to undergo a process of selecting which dependent variables would be used in statistical analysis and to pool data from 1999 and 2000. The full set of dependent variables was:

Cation Exchange: Al, Ca, Fe, K, Mg, Mn, Na, ECEC, and base saturation

Total Composition: Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, and Zn

Other Soil Properties: bulk density, pH_{H20}, pH_{CaCl2}, NO_3-N, NH_4-N, %C, %N, C:N

One of the assumptions of analysis of variance is that there be no pattern in missing data (Tabachnick and Fidell 2001). Three variables were not considered for use in statistical analysis because they violated this assumption: total Cd, and exchangeable Al and Fe. Values for total Cd obtained by HF digestion were below ICP detection limits in 2000. Exchangeable Al and Fe values which were below ICP detection limits were clustered in specific treatments.

In the end, seven dependent variables were selected for inclusion in statistical analysis: pH_{CaCl2}, ECEC, and total Na, Ca, P, K, and %N. These variables were selected because they are known to be of biological and ecological importance, hence changes in these variables are relevant to plant growth. Some of the variables were skewed and required transformation in order to satisfy MANOVA assumptions of normality (Tabachnick and Fidell 2001, Sokal and Rholf 1995). ECEC and total P were log-transformed (referred to as log ECEC and log total P) and reciprocals of total Ca and %N (referred to as recip. total Ca and recip. %N) were used to produce distributions which were as close to normal as possible. None of the variables had univariate or multivariate outliers. Most of these 7 dependent variables violated the assumption of homogeneity of variance, hence, Tahmane's T2 was used in post-hoc comparisons (where necessary) as it compensates for unequal variances. Games-Howell and Dunnett's T3 also compensate for unequal variances, but Tamhane's T2 produced the strictest results and was therefore the most cautious of the three test statistics. In the multivariate tests, Pillai's Trace was used as the approximation for statistical significance because it is the most robust when sample sizes are unequal (Tabachnick and Fidell 2001).

A multivariate significance test does not protect against inflated Type I error when using univariate tests for assessing between-subjects effects (Tabachnick and Fidell 2001, Weinfurt 1995). Tabachnick and Fidell (2001) recommend the following Bonferroni-type correction:

$$\alpha = 1 - (1- \alpha_1)\,(1- \alpha_2)\,(1- \alpha_3)\ldots\,(1- \alpha_p)$$

In this equation the number of alphas in the equation is the number of dependent variables being evaluated. Thus, for this study, the equation worked as follows:

$$\alpha = 1 - (1- \alpha_1)\,(1- \alpha_2)\,(1- \alpha_3)(1- \alpha_4)(1- \alpha_5)\,(1- \alpha_6)\,(1- \alpha_7)$$

$$\alpha = 1 - [(1\text{-}0.00731)]^7$$

$$\alpha = 0.0501$$

Hence, between-subjects effects were assessed as significant if p-values were at or below 0.0073.

Variables found to have significant between-subjects effects for Treatment were the only ones investigated with planned and post-hoc comparisons in this study. Attempting planned comparisons for both the differences between years and the differences between treatments would have spread experiment-wise alpha levels too thinly. Planned comparisons of differences between soil depths of dependent variables would not have been revealing since it is expected that soil properties differ with depth. Hence, only multivariate statistics and descriptive statistics for year and depth will be given.

Use of post-hoc comparisons requires α to be divided among the comparisons in order to maintain a Type I error rate of 0.05. In this study there would have been 15 post-hoc pair-wise comparisons and the Bonferroni correction would have been (Sokal and Rohlf 1995):

$$\text{comparison } \alpha = \frac{\text{experiment-wise } \alpha}{\text{number of comparisons}}$$

$$\text{comparison } \alpha = \frac{0.05}{15}$$

$$\text{comparison } \alpha = 0.003$$

An α of 0.003 has very low potential to reject a null hypothesis. The Dunnett method of multiple comparisons is a planned comparison which permits comparison of control and treatment means and does not require correction to maintain a Type I error rate of 0.05 (MacMillan, pers. comm. 2002, Glass and Hopkins 1984). Hence the Dunnett method was used to make the following comparisons:

H_1: S+T = CP
H_2: T = CP
H_3: B+S = CP
H_4: B = CP
H_5: S+T = OL
H_6: T = OL
H_7: B+S = OL
H_8: B = OL
H_9: CP = OL

Comparisons between experimental treatments were done post-hoc using the Bonferroni correction of α and the Tamhane's T2 test statistic. The post-hoc comparisons were as follows:

H_{10}: S+T = T
H_{11}: B+S = B
H_{12}: B+S = S+T
H_{13}: B = T
H_{14}: B+S = T
H_{15}: B = S+T

These post-hoc comparisons will use an α of 0.008 (0.05/6 = 0.008) as per the Bonferroni correction.

To summarize, traditional α of 0.05 was used for multivariate tests of significance, while between subjects were evaluated at 0.0073. Planned comparisons using the Dunnett can also be evaluated using an α of 0.05 and post hoc comparisons for experimental treatments were considered significant only if they had a result of less than or equal to 0.008. The pair-wise comparisons were based on pooled means for 1999 and 2000. If the data for the two years had not been pooled, the sample size would have been 3 for the reference plots and 6 for the experimental plots within each depth. Pooling the data for 1999 and 2000 gives a sample size of 6 for reference plots and 12 for experimental plots within each depth. The smallest sample size with years pooled (6 samples), still does not satisfy the rule mentioned above that sample size should be larger than the number of dependent variables, however running the model with smaller sub-sets of dependent variables did not cause changes in statistical significance of main effects, interactions, or pair-wise comparisons, hence the inversion matrix was stable (McMillan, pers. comm. 2002).

Values for eta squared (η^2) have also been provided in the statistical tables presented herein. The relative magnitude[5] of η^2 shows how much of the variance of a measure, or linear combination of measures, is the result of a main effect or interaction (Tabachnick and Fidell 2001). Kirk (1996) stressed that rejection or acceptance of a null-hypothesis is over-emphasized and that measures which provide an idea of the magnitude of effect of a treatment, like η^2, are more relevant in determining whether or not a procedure produced a difference in response.

3.3 Results

3.3.1 Statistical analysis

The MANOVA entered into SPSS for analysis of each depth was grouped data by Year, Landing, and Treatment. The dependent variables in the analysis were pH_{CaCl2}, log ECEC, total Na, recip. total Ca, log total P, total K, and log C:N. Levene's tests for homogeneity of variance were significant for all dependent variables ($p < 0.006$) except log ECEC ($p = 0.187$) in the analysis of 0-10 cm, for all dependent variables ($p < 0.028$) except log ECEC and log C:N ($p = 0.084$ and 0.389, respectively) in the analysis of 10-20 cm, and for all dependent variables ($p < 0.032$) except log C:N ($p = 0.616$) in the analysis of 20-30 cm. Hence, caution has been used in the statistical analysis in two ways: (1) where appropriate, the test statistics used do not assume equal variances, and (2) by employing strict α levels in between-subjects analysis, planned comparisons, and post-hoc comparisons (see section 3.2.6).

[5] Tabachnick and Fidell (2001) explain that values for eta squared can be directly translated to a percent of the variance explained only when dependent variables are uncorrelated.

Significance of Landing and interactions involving Landing were not reported as it is customary to ignore any significant differences between blocks. This is done for two reasons. First, the presence of an interaction in the error term makes it impossible to test the block mean squares over error mean squares. Second, there is a random restriction error associated with assigning treatments to blocks in a restricted complete randomized block and this causes there to be no appropriate mean square over which to test the block effect (Sokal and Rohlf 1995).

Omnibus MANOVAs for Year, Treatment, and Year x Treatment at each depth (Table 3.7) were significant ($p < 0.011$), with the exception of Year x Treatment of the 10-20 cm depth ($p = 0.485$). In the tests for between-subjects effects (Tables 3.8 to 3.10), Treatment was found to have a significant effect on the majority of the dependent variables for all depths, while Year and the interaction of Year and Treatment were found to be significant for only a few dependent variables. Results of analysis for between-subject effects, planned comparisons, and post-hoc comparisons for individual variables will be explained further in the following sections of descriptive statistics. Bear in mind when reading these sections that statistical analysis of differences between treatments was conducted on pooled data from 1999 and 2000 (see section 3.2.6).

3.3.2 Bulk density, total C, and pH

In 1999, biosolid-treated plots had the lowest bulk density (all layers < 1.34 g/cm^3), tillage-treated plots and the off-landing plot had an intermediate bulk density (all layers 0.99 to

1.95 g/cm^3), and the control plot had the highest bulk density overall with 1.45, 1.77, and 1.92 g/cm^3 in the 0-10, 10-20, and20-30 cm layers, respectively (Table 3.14). This pattern, biosolid-treated < tillage treated ≈ OL < CP (all layers) shifted slightly in 2000 so that biosolid-treated ≈ OL < tillage treated < CP (all layers). Bulk density typically increased with soil depth for all plots. No statistical analysis was done for differences in bulk density, hence it is not possible to say whether these observations were significant.

Statistical analysis of total C was not performed to verify the significance of the observations that follow. B+S plots typically had higher total C than did B plots (Figure 3.3). For example, at 10-20 cm in 2000, B+S had 5.61 %C while B had 3.39 %C. Biosolid-treated soil ranged from 5.21 to 11.67 %C in 1999 and from 0.97 to 16.16 %C in 2000. The highest observed %C for all other study plots was 5.72 for CP, 0-10 cm in 2000. Except for CP, 0-10 cm in 2000, the range in total C for tillage-treated and reference plots was 0.53 to 3.28 %C. For all study plots, total C tended to decrease with depth. S+T in 1999, for example, had 1.94 %C in the 0-10 cm layer and 0.72 %C in the 20-30 cm layer. Only biosolid-treated plots had notable differences between years in total C, however, they had no consistently identifiable trends in whether 1999 or 2000 had a higher %C.

General trends in pH were the same whether measured in water (Figure 3.4) or $CaCl_2$ (Figure 3.5) although the mean pH_{CaCl2} was lower. Mean pH_{CaCl2} was approximately 0.25 to 0.50 pH units lower than pH_{H20} in biosolid-treated plots, 0.45 to 0.90 pH units lower on S+T, T, and CP, and 0.05 to 0.80 pH units lower for OL. Using $\alpha = 0.008$ and examining pair-wise comparisons for each depth, biosolid-treated plots generally had a significantly higher pH_{CaCl2}

than the tillage-treated plots ($p < 0.002$, Tables 3.11 to 3.13 and 3.16). The exceptions were the comparisons of B+S and T for 10-20 cm and 20-30 cm, which were not significant ($p = 0.036$ and 0.011, respectively). Seeded plots had a slightly lower pH than unseeded plots. For example, in 1999, B+S had a pH of 6.70 or 6.45 in the 0-10 cm layer with pH_{H2O} and pH_{CaCl2} respectively, while B had a pH of 6.85 or 6.50 with pH_{H2O} and pH_{CaCl2}, respectively. However, the difference between seeded and unseeded plots, both biosolid and tillage-treated, was not found to be significant for any of the three depths ($p > 0.426$, Tables 3.11 to 3.13 and 3.16). To summarize for both years:

pH: OL < CP ≈ tillage-treated < biosolid-treated.

CP and OL were significantly different for 0-10 cm ($p = 0.011$), but not for 10-20 and 20-30 cm ($p = 0.354$ and 0.564, respectively). Comparisons of pH of B+S or B with CP or OL were significant for each depth ($p < 0.001$). Differences between S+T or T and CP, at any depth, were generally non-significant ($p > 0.560$). T was found to be significantly different when compared with OL at all depths ($p < 0.003$). S+T was found to be significantly different from OL in the 10-20 cm soil layer ($p = 0.037$) but differences in 0-10 and 20-30 cm layers were non-significant ($p = 0.051$ and 0.564, respectively).

Using $\alpha = 0.00731$ for between-subjects effects in all three depths, Year did not have a significant effect on pH, nor did the interaction of Year and Treatment (Tables 3.8 to 3.10). Accordingly, the amount of variance in Year and the amount of variance in the interaction of Year and Treatment that could be explained by pH was low ($\eta^2 < 0.114$ for all depths). Conversely, pH had consistently high η^2 values for Treatment ($\eta^2 > 0.725$ for all depths).

3.3.3 Exchangeable cations

Statistical analysis was not applied to individual exchangeable cations; therefore, all trends referred to in the following section are based on descriptive statistics. ECEC was statistically analyzed and results of that analysis are presented with the descriptive statistics.

Exchangeable Ca and exchangeable Na were higher for biosolid-treated plots than tillage-treated or reference plots in both years (Figures 3.6 and 3.7). The difference between biosolid-treated plots and other plots decreased with depth, especially in 2000. However, the difference between biosolid-treated and other study plots was always noticeable. For example, in 2000 the biosolid-treated plots had a range of 0.15 to 0.18 $cmol_+$ Na/kg across all depths while the next highest group, the tillage-treated plots, had a range of 0.14 to 0.15 $cmol_+$ Na/kg. Exchangeable Ca decreases with depth for all study plots, but consistent depth-related trends were not present in $cmol_+$ Na/kg on the tillage-treated or reference plots. To summarize trends for exchangeable Na and Ca:

exchangeable Na and Ca: 1999 > 2000.
exchangeable Ca in 1999: OL $\approx$ CP $\approx$ tillage-treated << biosolid-treated
exchangeable Na in 1999: OL $\approx$ CP $\approx$ tillage-treated << biosolid-treated
exchangeable Ca in 2000: OL $\approx$ CP $\approx$ tillage-treated < biosolid-treated
exchangeable Na in 2000: OL $\approx$ CP < tillage-treated < biosolid-treated

Exchangeable Mg was higher on biosolid-treated plots than tillage-treated plots in 1999 (Figure 3.8). Biosolid-treated plots had between 5.06 and 7.54 $cmol_+$ Mg/kg in 1999, and tillage-treated plots had between 3.09 and 3.15 $cmol_+$ Mg/kg. In 2000, the difference between tillage-treated and biosolid-treated plots was reduced. Variability of the exchangeable Mg of biosolid and tillage-treated plots obscured differences between treatments below 0-10 cm. In general, the trend of exchangeable Mg with depth observed on an individual plot seemed to be preserved between the two years: if a plot increased in exchangeable Mg with depth in 1999, then the pattern was repeated in 2000. Differences between seeded and unseeded plots in exchangeable Mg increased with depth. For both years, B+S had less exchangeable Mg in comparison to B as depth increased. The difference between B+S and B treatments in 1999 in the 0-10 cm layer was 0.37 $cmol_+$ Mg/kg, and for the 20-30 cm layer the difference was 2.7 $cmol_+$ Mg/kg. In 1999, S+T had less exchangeable Mg relative to T as depth increased, but in 2000, S+T had more exchangeable Mg relative to T as depth increased.

For exchangeable Mn, there was no obvious difference caused by the application of biosolids or seeding of a fallow crop, nor was there a consistent trend with depth even when individual treatments were compared between years (Figure 3.8). Overall, there was a decrease in the amount of exchangeable Mn between 1999 and 2000. For example, in the 0-10 cm layer, biosolid-only treated plots had a mean $cmol_+$ Mn/kg of 0.11 in 1999 and 0.07 in 2000. B, CP, and OL plots generally had lower exchangeable Mn than the other plots, with the exception of OL 0-10 cm, which had a relatively high amount of exchangeable Mn (0.27 and 0.39 $cmol_+$ Mn/kg for 1999 and 2000, respectively).

Exchangeable K was higher for biosolid-treated plots than tillage-treated or reference plots in 1999 (Figure 3.10). Although all depths decreased somewhat in $cmol_+$ K/kg with depth, the difference between biosolid-treated plots and other plots decreased with depth in 1999. However, it was still possible to see an effect due to biosolid-treatment in the 20-30 cm layer: minimum $cmol_+$ K/kg in the biosolid-treated plots was 0.40 and the maximum amount of all other plots was 0.35 $cmol_+$ K/kg. In 2000, there was no difference between the tillage-treated and biosolid-treated plots by the depth of 10-20 cm. Exchangeable K for a given treatment was typically higher in 1999 than in 2000. Other observable trends in exchangeable K were:

1999: CP < OL ≈ tillage-treated << biosolid-treated
2000: OL < CP < tillage-treated < or ≈ biosolid-treated

The amount of exchangeable Al was much higher on OL compared to all other plots in both years (Figure 3.11). Maximum $cmol_+$ Al/kg on plots other than the OL was only 177×10^{-3} $cmol_+$ / kg, but the minimum amount for the OL was 1028×10^{-3} $cmol_+$ Al/kg. Exchangeable Fe in OL was also much higher compared to almost all other plots for both years (Figure 3.12), but the scale of the difference was much lower than for exchangeable Al. For exchangeable Fe, the B+S treatment also had very high observed values in 1999 that did not decrease noticeably with depth (the range in B+S across depths was 185×10^{-3} to 233×10^{-3} $cmol_+$ Fe/kg). In general:

exchangeable Al (1999): biosolid-treated < tillage-treated < CP << OL
exchangeable Al (2000): biosolid-treated < T < CP < S+T << OL
exchangeable Fe (1999): B ≈ CP < or ≈ tillage-treated << OL or B+S
exchangeable Fe (2000): biosolid-treated < CP < or ≈ tillage-treated << OL

There was also an overall decrease in exchangeable Al and Fe with depth on the majority of plots, but the trend was masked by the scale of the graph.

In statistical analysis, there were significant differences in log ECEC for Year in the 20-30 cm layer ($p = 0.003$, Table 3.10), but not for 0-10 and 10-20 cm ($p = 0.017$ and 0.008, respectively, Tables 3.8 and 3.9). The η^2 of log ECEC for Year at each depth was intermediate compared to other values of η^2 for Year and it ranged from 0.134 to 0.200. The interaction of Year and Treatment was not significant for log ECEC at any depth

($p > 0.058$). Differences between Treatments for log ECEC were significant ($p < 0.001$) and these differences were associated with high η^2s (0.858, 0.641, and 0.420 for 0-10, 10-20, and 20-30 cm, respectively).

ECEC decreased with depth on the biosolid-treated plots but no decrease with depth was seen in other treatment and reference plots (Figure 3.13). As a result, plots became more similar in ECEC with increased depth: 9 of 15 pair-wise comparisons were significant in the 0-10 cm layer (Tables 3.12 and 3.17) and only 4 of 15 pair-wise comparisons were significant in the 20-30 cm layer (Tables 3.14 and 3.17). There was a decrease in ECEC for the biosolid treated plots between 1999 and 2000, but not a notable decline for the tillage-treated or reference plots between years. The range of ECEC for the biosolid-treated plots in 1999 was 21.4 to 41.9 $cmol_+/kg$ and in 2000 it was between 12.8 and 40.2 $cmol_+/kg$, showing that the minimum amount in 2000 was more extreme. The range for tillage-treated and reference plots, on the other hand, was between 5.87 and 13.1 $cmol_+/kg$ in 1999 and between 4.92 and 11.03 $cmol_+/kg$ in 2000, representing a less severe shift than seen for the biosolid-treated plots. However, as mentioned above, these differences for Year, were not significant.

Between-plot trends for ECEC were as follows:

1999: CP < S+T < OL < tillage-treated << biosolid-treated
2000: OL < CP < tillage-treated < biosolid-treated

The means of seeded and unseeded plots were not significantly different from each other. For all depths, comparisons of B+S and B had p-values of > 0.079 and comparisons of S+T and T had p-values of 1.000 (Tables 3.11 to 3.13 and 3.16). CP and OL plots were also not found to be significantly different from each other ($p > 0.299$). In the

0-10 and 10-20 cm layers, pair-wise comparisons of S+T or T with OL or CP were not consistently significant or non-significant (Tables 3.11, 3.12, and 3.16). Comparisons of S+T, T, OL, and CP in the 20-30 cm layer were non-significant ($p > 0.122$). B+S and B were significantly different from the reference plots at all depths ($p < 0.006$). B+S and B were also significantly different from S+T and T for the upper two soil layers ($p < 0.001$), but were not significantly different in the 20-30 cm layer ($p > 0.044$).

Base saturation was stable from year to year for a given plot, hence the pattern OL < CP ≈ tillage-treated < biosolid-treated, holds true for both years (Table 3.10), but this is a subjective trend as statistical analysis was not applied to base saturation. OL was the most unique of all study plots with a range of 80.86 to 96.02% base saturation while all other study plots had a range of 95.21 to 99.63% base saturation. Most plots had a decrease in base saturation with increasing depth, however the OL is unique again in this regard: its base saturation increased with depth.

3.3.4 Selected macronutrients (N, P, K, Mg, Ca)

Although statistics were not used for NH_4-N and NO_3^-N, trends in concentration appear to have been the same for available soil NH_4-N and NO_3^-N in 1999 and 2000: CP ≈ OL ≈ tillage-treated << B < B+S (Figures 3.14 and 3.15). With the exception of NH_4-N in 1999, the degree of difference between biosolid and tillage-treated plots decreased with depth because available NH_4-N and NO_3^-N decreased depth on the biosolid-treated plots. For example, in 1999, mean NO_3^-N concentrations found in B+S, 0-10 and 20-30 cm, were

246 and 22 µg/g, respectively, while CP had approximately 5 µg NO_3^-N/g for 0-10 and 20-30 cm. In the case of NH_4-N in 1999, concentration for B+S increased with depth, and for B the concentration of NH_4-N was highest in the 10-20 cm depth. Tillage-treated and reference plots showed decreases in NH_4-N with depth (albeit very slight in some cases), but for NO_3^-N in these plots, there tended to be a maximum value in the 10-20 cm layer and the lowest value in the 20-30 cm layer (i.e., OL in 2000, 0-10, 10-20, and 20-30 cm had 0.78, 2.01, and 0.24 µg NO_3^-N/g, respectively).

Statistical analysis found significant differences in Treatment for log C:N in all depths ($p < 0.001$, Tables 3.9 to 3.11). The values of η^2 corresponding to these differences were moderate to high ($\eta^2 = 0.657$, 0.406, and 0.397 for 0-10, 10-20, and 20-30 cm, respectively) in comparison to other η^2s for Treatment. Year and the interaction of Year and Treatment were non-significant for log C:N ($p > 0.045$) and the η^2 values for Year and Year x Treatment were small (η^2 ranged from 0.001 to 0.097).

On tillage-treated and reference plots, C:N decreased with depth, while for the biosolid-treated plots it tended to increase with depth (Figure 3.16). All plots became more similar in C:N as depth increased: 7 of 15 pair-wise comparisons were significant in the 0-10 cm layer and 2 of 15 pair-wise comparisons were significant in the 10-20 and 20-30 cm layers (Tables 3.11 to 3.13, and 3.16). In 1999 and 2000, the C:N of OL and CP were approximately the same (i.e. ranging from 15.2 to 27.8 in 1999) as the tillage-treated plots (i.e. ranging from 21.6 to 39.2 in 1999). Accordingly, pair-wise comparisons of OL, CP, S+T, and T, were non-significant for all depths ($p > 0.087$). Biosolid-treated plots were generally found to be significantly different from CP and OL in only the 0-10 cm layer ($p < 0.004$). The exception was B+S and CP in the 20-30 cm layer ($p = 0.001$). In both years, C:N of the biosolid-treated plots was lower than that of the tillage-treated plots although this difference was less distinct in 2000 (Figure 3.16). Statistically, for 0-10 and 10-20 cm layers, B+S and B were generally found to be significantly different from tillage-treated plots, but not from each other (Tables 3.11, 3.12 and 3.16). The highest observed C:N in 2000 was from OL in the 0-10 and 10-20 cm layers (C:N of 42.1 and 26.4, respectively). OL had an intermediate C:N of 20.1 in comparison to the other plots in the 20-30 cm layer.

Total P concentrations for the tillage-treated and reference plots were stable over the two years and did not change dramatically with depth (Figure 3.17). In 1999, the range of total P was between 709 and 1271 μg/g for the tillage-treated and reference plots, which was roughly the same as the range of 603 to 1338 μg/g for 2000. These observations were in agreement with the statistical analysis. There were no significant differences between years for log P ($p > 0.011$), and with few exceptions, pair-wise comparisons of tillage-treated and reference areas were non-significant (Tables 3.11 to 3.13, and 3.16). Log total P had significant differences in Treatment for all depths ($p < 0.001$, Tables 3.8 to 3.11) and in Year x Treatment for 0-10 cm ($p < 0.001$). The η^2s of Log P for Treatment were moderate relative to other η^2s for Treatment (0.794, 0.604, and 0.400, for 0-10, 10-20, and 20-30 cm soil depths, respectively). Log P had high η^2s, relative to other η^2s for Year x Treatment ($\eta^2 > 0.296$) and η^2s ranging from low to moderate for Year (0.150, 0.036, and 0.129, for 0-10, 10-20, and 20-30 cm, respectively).

The biosolid-treated plots had far higher total P concentrations than the other plots, especially in 2000 when the concentrations were between 2511 and 1928 μg/g on biosolid-treated plots and the highest total P concentration for all other plots was 1271 μg/g. Biosolid-treated plots showed a decrease in P content with depth whereas other plots did not. For example, B in 2000, 0-10 cm and 20-30 cm had 3597 and 1089 μg P/g, respectively, which represents a decrease of 30%. OL in 2000, in contrast, had an increase in total P with depth (863 and 977 μg P/g for 0-10 cm and 20-30 cm, respectively). For all depths in general:

1999: T < or ≈ OL < S+T < or ≈ CP << B < B+S
2000: S+T < or ≈ T ≈ OL < or ≈ CP < B << B+S

The preceding observations regarding trends with depth and comparisons of B+S and B were reflected in the statistical analysis. B+S and B were not found to be significantly different from each other but were found to be significantly different from the control plots and tillage-treated plots in the 0-10 and 10-20 cm layers (Tables 3.11, 3.12, and 3.16). The only pair-wise comparisons found to be significantly different in the 20-30 cm layer were B+S and OL ($p = 0.039$) and CP and OL ($p = 0.009$, Tables 3.13 and 3.16). The 20-30 cm layer was the only one in which CP and OL were found to be significantly different.

As a result of there being an increase in K concentration between 1999 and 2000 on almost all plots, Year was statistically significant for total K at all depths ($p < 0.001$, Tables 3.8 to 3.10) and these significant differences were associated with the highest observed η^2s for Year ($\eta^2 = 0.466$, 0.741, and 0.608, for 0-10, 10-20, and 20-30 cm soil depths, respectively). The interaction of Year and Treatment was not significant for total K ($p > 0.083$). Treatment was significant for total K only in the 0-10 and 10-20 cm soil layers ($p < 0.001$ for 0-10 and

10-20 cm, $p = 0.538$ for 20-30 cm; Tables 3.8 to 3.10). The amount of variance in Treatment explained by total K was among the lowest observed ($\eta^2 = 0.540$, 0.459, and 0.052 for 0-10, 10-20, and 20-30 cm soil layers, respectively; Tables 3.8 to 3.10). The only significantly different treatments in pair-wise comparisons for the 0-10 cm soil layer (Table 3.11) were B+S and CP ($p = 0.002$) and B+S and S+T ($p = 0.007$), and in the 10-20 cm layer, only B+S and CP were significantly different ($p = 0.027$, Table 3.12). These results for treatment were not unexpected given that the range in observed mean total K for all plots was not very large and that there was little change in total K with depth (Figure 3.18). In 1999 total K for all plots ranged from 10 to 16 mg/g while in 2000, it ranged from 10 to 18 mg/g. Overall trends for total K concentration were:

1999: B+S < B < OL ≈ CP < T < S+T
2000: B+S < B < OL < CP < S+T < CP

Values for mean total Mg had a narrower range in 1999 than in 2000 (Figure 3.19). The range in 1999 was from 7.8 to 9.6 mg Mg/g while in 2000 mean total Mg had a minimum of 7.0 mg/g and a maximum of 10.7 mg/g. Differences between treatments in total Mg were not statistically analyzed, however visual inspection of Figure 3.19, shows that total Mg was generally higher on tillage-treated and reference plots than on biosolid-treated plots, with the exception of the 20-30 cm layer in 2000. Biosolid-treated plots had an increase in Mg content with depth in both years. The quantity of total Mg on tillage-treated plots decreased slightly with depth or remained about the same in both years. OL and CP had the same general trend with depth as tillage-treatment plots: decreasing slightly with depth or remaining about the same. There was no major change between the years for Mg content. Total Mg was not subject to statistical analysis therefore these trends were subjective.

The amount of total Ca was higher on biosolid-treated plots than tillage treated plots (Figure 3.20). The tillage-treated and reference plots had similar total Ca concentrations: the range of total Ca for tillage-treated plots across years and depths was 13.6 to 15.2 mg/g while for the reference plots it was 14.0 to 16.1mg/g. Statistical results supported the identification of these trends. In the 0-10 and 10-20 cm layers, S+T, T, OL and CP were found to have no significant differences in pair-wise comparisons, comparison of B+S and B was non-significant, and comparison of B+S or B with tillage-treated and reference plots was usually significant (Tables 3.11, 3.12, and 3.16). The difference between biosolid and tillage-treated plots decreased with depth, and only 2 of 15 pair-wise comparisons in the 20-30 cm layer were found to be significant (Tables 3.13 and 3.16). Only the 10-20 and 20-30 cm depths for the biosolid-treated plots showed a decrease in Ca content between 1999 and 2000. Accordingly, Year and Year x Treatment were not significant for recip. total Ca and η^2 values for Year and Year x Treatment for recip. total Ca were some of the smallest observed (Tables 3.8 to 3.10).

3.3.5 Selected micronutrients (Cu, Zn, Fe, and Mn)

Statistical analysis was not conducted on any of the micronutrients, therefore trends referred to in the following section were subjective interpretations of descriptive statistics.

With the exception of CP, 0-10 cm, 1999, mean total Cu of biosolid-treated plots was far higher than that of tillage-treated and reference plots (Figure 3.21). Copper concentration in the biosolid-treated plots varied from 58 to 992 μg Cu/g over both years and all depths while the tillage-treated and reference plots (CP, 0-10 cm, 1999 excepted) range from only 12 to 59 μg Cu/g. The same was true for total Zn (Figure 3.22): concentrations were higher on biosolid-treated plots than tillage-treated and reference plots. Mean total Zn in the biosolid-treated plots varied from 157 to 543 μg/g over both years and all depths while the tillage-treated and reference plots had a range of 68 to 216 μg Zn/g. Cu content in 1999 and 2000 was approximately the same for each plot while Zn concentration was generally higher for each plot in 2000 than in 1999. Cu and Zn content of the biosolid-treated plots decreased with depth. There were no consistent trends with depth for reference or tillage-treated plots with either element. To summarize:

total Cu: 1999 ≈ 2000
total Cu 1999: OL ≈ CP ≈ tillage-treated << biosolid-treated
total Cu 2000: OL < CP ≈ T < B < B+S

total Zn: 1999 < 2000
total Zn 1999: S+T < T ≈ OL ≈ CP << biosolid-treated
total Zn 2000: OL ≈ CP≈ tillage-treated < B < B+S

Mean total Fe (Figure 3.22) was lower for the biosolid-treated plots than the tillage-treated plots. This trend tapers off with depth: concentrations on the tillage and biosolid plots are nearly equivalent by the 20-30 cm layer. For example, in 2000, the 0-10 cm layer had 24.7 and 35.6 mg Fe/g for B+S and T plots, respectively; whereas the 20-30 cm layer had 36.5 and 36.4 mg Fe/g for B+S and T plots, respectively. Tillage-treated plots had a slight increase in mean total Fe with depth or remained about the same across all depths. For the most part, seeded treatments had lower total Fe than unseeded treatments but the difference between seeded and unseeded was less noticeable for tillage-treated plots than biosolid-treated plots. In 1999, the reference plots had slightly higher mean total Fe than the tillage-treated plots, while in 2000, the reverse was true (i.e., in 2000, Fe concentrations in the 10-20 cm layer were between 30.6 and 33.6 mg/g on reference plots and 36.7 to 39.2 mg/g in tillage-treated plots). Mean total Fe was generally higher in 2000 on all plots.

Comparing plots within a given depth, total Mn in the soil was slightly higher on biosolid-treated plots than tillage-treated plots and reference plots in 1999, but not in 2000, with the exception of B+S, 0-10 cm (Figure 3.23). As an example, for 20-30 cm, the lowest observed value for a biosolid-treated plot was 673 μg Mn/g and the tillage-treated plots had a maximum of 649μg Mn/g in 1999, whereas in 2000 the lowest observed value in a biosolid-treated plot at 20-30 cm was 771 μg Mn/g and the highest tillage-treated value was 769 μg Mn/g. In the majority of cases, the reference plots had lower Mn levels than the experimental plots. Virtually all plots at all depths had an increase in Mn between 1999 and 2000. OL, 0-10 cm, for example, had total Mn concentrations of 546 and 746 μg/g for 1999 and 2000, respectively. There was no trend with depth within plots or between years. Looking at both years, in the 0-10cm layer B+S treatment had a higher Mn concentration than B but this was reversed in the 10-20 and 20-30 cm layers. In 1999, S+T had higher amounts of Mn than T, and in 2000 this was reversed.

3.3.6 Other elements (Na, Al, Ni, Cr, and Cd)

Mean total Na was the only element in this section for which statistical analysis was conducted. The concentration of total Na was higher on tillage-treated and reference plots than on biosolid-treated plots (except for the 20-30 cm layer in 2000, Figure. 3.24). To illustrate this difference, the range of mean total Na for biosolid-treated plots in 1999 (all depths) was 13.6 to 16.3 mg Na/g while the minimum mean total Na on tillage-treated or reference plots in 1999 (all depths) was 17.7 mg Na/g. Accordingly, in the 0-10 cm layer, pair-wise comparisons of B+S or B with S+T, T, OL, and CP were generally found to be significant, while S+T and T were not found to be significantly different from the control plots, and the control plots were not significantly different from each other (Tables 3.11 and 3.16). However, in the 10-20 cm soil layer, only B+S and CP were found to be significantly different ($p = 0.002$, Tables 3.12 and 3.16), and Treatment was not significant for total Na in the 20-30 cm soil layer ($p = 0.538$, Tables 3.10 and 3.16).

Statistically, the changes in Na concentration between years were significant for 10-20 and 20-30 cm layers ($p < 0.001$, Tables 3.9 and 3.10) although changes in total Na content with depth were not necessarily the same in both years. Biosolid-treated plots had an increase in total Na content with increasing depth in both years. The quantity of Na in tillage-treated plots decreased slightly with depth or remained about the same in both years. OL and CP had decreases in Na with depth in 2000 but increased with depth in 1999. However, Year x Treatment was not found to be significant for total Na, although the η^2s of total Na for the interaction were high relative to other η^2 values for Year x Treatment.

Between 1999 and 2000, most plots had an increase in Na but the degree of difference between the two years decreased with depth. The range of total Na for all plots in the 0-10 cm layer for 1999 was 13.6-19.2 mg/g, and 9.2-24.3 mg/g in 2000. Both years were very similar at the depth of 20-30 cm, however, with 16.3-22.9 mg Na/g and 21.8-24.3 mg Na/g for 1999 and 2000, respectively, across all treatments (which is in accordance with the lack of significant differences between treatments for the 20-30 cm layer mentioned above).

Total Al was lower for the biosolid-treated plots than the tillage-treated plots (Figure 3.25), however the extremity of this difference decreased with depth and total Al concentrations on the tillage and biosolid plots were nearly equivalent at 20-30 cm. In 1999, Al concentrations in the 10-20 cm layer were between 63.1 and 66.2 mg/g on the reference plots and 59.4 to 62.3 mg/g in tillage-treated plots. In 2000, OL and CP had slightly lower Al than the tillage-treated plots. For biosolid-treated plots, the amount of Al increased with depth while tillage-treated plots had a slight increase in total Al with depth or remained about the same across all depths. Seeded treatments generally had lower total Al than unseeded, but the difference is very slight. For example, the S+T and T plots in 1999 at the depth of 20-30cm had 61.3 and 62.9 mg Al/g, respectively. For all plots and depths, total Al was greater in 2000 than in 1999.

For total Ni, there were no consistent trends between and within experimental plots when compared between the two years (Figure 3.26). The reference plots tended to have lower Ni content compared to the experimental plots but this trend was not present at all times. One identifiable general trend was a decrease in Ni content between 1999 and 2000. For example, the 20-30 layer of the off-landing plot had 69.0 μg Ni/g in 1999 and 46.3 μg Ni/g in 2000.

In 1999, total Cr content was roughly the same for all treatments and depths with a range of 110 to 137 μg/g (Figure 3.27). In 2000 differences between treatments became more pronounced in the 0-10 cm layer where tillage-treated plots had the highest Cr content with just over 120 μg Cr/g, while biosolid-treated and reference plots had noticeably less Cr (< 110 μg Cr/g). For the 10-20 cm layer in 2000, tillage-treated plots still had the highest Cr contents, but the degree of difference between plots was decreased in comparison to the 0-10 cm layer (OL excepted). In the 20-30 cm layer in 2000, biosolid-treated plots and OL had the most Cr (120, 120, and 136 μg/g for OL, B+S, and B, respectively). Off-landing and control plots had Cr contents that increased with depth, as did most of the experimental plots in 2000.

Total Cd concentrations were below detection limits in 2000. In 1999 the total Cd content of B+S plots was less than that of B by a difference of 0.24 μg/g in the 0-10 cm layer, 0.54 μg/g in the 10-20 cm layer, and 2.41 μg/g in the 20-30 cm layer (Figure 3.28). S+T had higher amounts of Cd than T (i.e. at a depth of 10-20 cm, the S+T plot had 4.33 μg Cd/g, while T had 3.78 μg Cd/g). Cadmium concentrations of soils in the control plot increased dramatically with depth: from 2.25 μg/g at 0-10 cm, to 5.62 μg/g at 20-30 cm. For OL, Cd content was generally high to moderate compared to all other plots.

3.4 Discussion

3.4.1 Bulk density, total C, and pH

Bulk density of biosolid-treated plots remained approximately the same for 0-10 cm between the two years, however, in the 10-20 and 20-30 cm ranges, bulk density was higher in 2000 than in 1999 on the biosolid-treated plots. It is likely that this increase in bulk density was due to settling of the biosolid material. Despite this increase, the biosolid treated soil below 10 cm still had a bulk density much lower than control and tillage-treated plots, and lower than bulk densities obtained by researchers using other reclamation methods. The average bulk density of 0-10, 10-20, and 20-30 cm soil layers of biosolid-treated plots in either year ranged from 0.67 to 1.04 g/cm^3 (B+S in 1999 and B in 2000, respectively) in this study. The lowest bulk density observed by Kranabetter and Osberg (1995) with stockpiled topsoils respread on decompacted landing areas was 1.240 g/cm^3. Their level of recompaction following ripping[6] and topsoil respreading was only slightly greater (0.07 to 0.32 g/cm^3 increase, 0-30 cm) than the average increases following biosolid addition in this study (0.27 and 0.10 g/cm^3 for B+S and B, respectively). Kranabetter (1990) applied pulp mill biosolids to ripped landings at a rate of approximately 51 Mg/ha to a depth of 10 cm and found that the treatment resulted in a bulk density of 1.1 g/cm^3. The present study had a higher rate of biosolid application than that of Kranabetter (1990) therefore, it is not unexpected that the bulk density found by Kranabetter (1990) is higher than that of this study. While statistical analysis was not done on bulk density data in this study, it is likely that the outcome would have been significant given subjective analysis of the descriptive statistics for bulk density.

Standard errors for bulk density of OL soil tended to be high. The presence of buried slash and roots may have been responsible for this error and resulted in the instability of results in bulk density between years for OL. Kranabetter and Osberg (1995) found bulk densities of 1.185 to 1.545 g/cm^3 (0-30 cm) in their undisturbed reference plots, which is similar to the bulk density of the OL in the present study.

Landing area soil bulk densities reported by Kranabetter and Osberg (1995) were also similar to those found in this study. Their untreated landing areas had bulk densities of between 1.720 and 1.825 g/cm^3 (0-30cm) while the average bulk density of the 0-10, 10-20, and 20-30 cm soil layers analyzed in this study were 1.71 and 1.64 g/cm^3 in 1999 and 2000, respectively. Kranabetter (1990) also found landing area bulk densities in accordance with those found in this study, as were the winter-constructed landings in the studies by Carr (1987a and 1988). The percent increase in soil bulk density of landings in comparison to off-landing plots for Carr (1987a) were 89, 54, and 43% for 0-10, 10-20, and 20-30 cm depths in the soil profile of a summer-constructed landings and 66, 36, and 26% for 0-10, 10-20, and 20-30 cm depths in the soil profile of a winter-constructed landings. In the present study, when the increases in bulk density of CP over OL in 1999 and 2000 are averaged, the corresponding increases in bulk density for 0-10, 10-20, and 20-30 cm depths were: 58, 51, and 7%.

On two of their three study sites, Kranabetter and Osberg (1995) found that one year after

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[6] Ripping refers to a tillage-type treatment using a winged subsoiler in order to decompact a landing (Kranabetter and Osberg 1995).

ripping landing areas, the soils had recompacted to a bulk density similar to untreated landings. Recompaction was not found to be a problem in the present study even though, like Kranabetter and Osberg (1995), the landings being studied had medium-textured soil. Kranabetter and Osberg (1995) concluded that the success of their treatments was hampered by the fact that the soil was wet when decompacted. Perhaps the present study was more successful because tillage was done when the soil of the landing was dry.

Linear relationships have been shown to exist between organic matter content, total C, and bulk density of soils (Huntington et al. 1989). Incorporation of organic matter into the soil by biophysical processes contributes to soil stability and development of soil structure (Juma 1994, Brady and Weil 1999), therefore increases in soil organic matter content or total carbon content are associated with each other and will correspond to decreased soil bulk density (Huntington et al. 1989). Although statistical analysis of the relationship between bulk density and total C was not conducted in the present study, biosolid-treated areas did tend to have a higher total C and lower bulk density while tillage-treated areas had a lower total C and higher bulk density (Figure 3.3 and Table 3.14). Coincidentally, the decrease in bulk density of the OL in 0-10 and 10-20 cm layers from 1999 to 2000 is associated with a notably higher total C content in 2000 than in 1999 for the 0-10 cm layer.

The pH of biosolid-treated plots was higher than other study plots in 1999 and 2000 and it did not decrease in 2000. Other authors have observed decreases in pH as a result of municipal biosolids addition (Harrison et al. 1996, Chang et al. 1983). These studies cited nitrification as the likely source of H^+. Studies using pulp and paper mill biosolids, however, have been associated with increased soil pH (Kraske and Fernandez 1993, Brockway 1983). There are several potential explanations for why there was no decrease in pH from papermill and municipal biosoids addition. Adding clarifier waste may have prevented the decrease in pH associated with municipal biosolids addition by slowing the decomposition process and increasing the buffering power of the soil by raising CEC. Hue et al. (1988) also found an initial increase in pH for 3 different soils as a result of municipal biosolid application and they cited increased CEC as the source of the increased pH. Root respiration and anion exchange, which both give off bicarbonate and therefore increase the pH of the root zone (Barber 1995), may have compensated for acid production by the nitrification process. However, if root respiration and anion exchange were the main cause of increased pH in this study, then the pH of B+S would have been higher than that of B. Instead, the pH of B+S was lower than that of B. Primary pulp and paper mill wastes contain high amounts of calcium carbonates (Anon. 1989), therefore the carbonates present in the biosolid-treatment may have had a liming effect (Barber 1995). It may simply take a few more years for the decrease in pH associated with municipal biosolid addition to occur, or the system may continue being buffered by the properties of the pulp and paper mill biosolids.

3.4.2 Exchangeable cations

It is not surprising that the quantity of exchangeable cations and ECEC were higher for experimental plots in 1999 than in 2000. Quantities of exchangeable cations on biosoid-treated plots will have been higher in 1999 because of substantial additions of nutrients and trace elements. In tillage-treated plots, quantities of excha ngeable cations will have been increased because tillage stimulates microbial activity by disrupting soil aggregates and by increasing the available surface area of previously inaccessible soil organic matter. Tillage also makes soil conditions more favourable for microbial growth by improving soil properties such as aeration and hydraulic conductivity (Paul and Clark 1996). Increased ECEC after tillage in comparison to pre-treatment ECEC could therefore have been brought about by increased mineralization providing more available cations, and/or by exposing more functional groups on the organic matter present in the soil.

In B plots, decreased ECEC in 2000 in 10-20 and 20-30 cm layers was most likely brought about by leaching of cations not taken up by plants or microorganisms. Given the high density of grasses on B+S plots, the decrease in ECEC may have been caused by plant uptake of exchangeable cations. Leaching or uptake of cations does not reduce ECEC per se, but these mechanisms could make the ECEC appear to be reduced by removing exchangeable cations from the exchange complex and therefore making displacement measures of ECEC, like barium chloride, appear to be lower. For tillage-treated plots, loss of exchange sites due to decomposition of organic matter is an unlikely explanation because organic matter brought to the surface by tillage is probably resistant to decomposition. For tillage-treated areas, reduced ECEC was likely the result of re-immobilization of cations initially released in mineralization of organic matter made accessible by tillage, which again is a mechanism would make ECEC as measured by barium chloride appear to be lower even though roughly the same number of exchange sites may be present.

Decreases in pH are associated with decreases in CEC (Brady and Weil 1999), however ECEC of B+S was higher than B, despite B+S having a lower pH. It could be that the soil of B+S had more microbiological activity than B, causing decomposition rates to be higher and therefore causing ECEC and the pool of exchangeable cations to be larger. The higher ECEC of T compared to S+T in 1999 is probably a co-incidence since differences in plant cover between these two sites was minimal in 1999 (data not presented) and the trend does not persist in 2000.

In quantity of exchangeable cations, biosolid-treated plots become more similar to other study plots with depth. This is a reflection of the fact that the amount of biosolids added decreased with depth. As the quantity of biosolid in the biosolid-soil mixture decreased, the characteristics of biosolid-amended soil become more similar to that of the tillage-treated and reference plots soils. A study by Harrison et al. (1994), where 400-600 Mg/ha anaerobically digested sewage sludge was disked into the soil to a depth of 30cm, also found decreasing difference in soil properties between treated and control plots with increasing depth, finding almost no differences below 17 cm and no differences below 27 cm.

Differences in exchangeable cations between the 1999 and 2000 could also have been a result of the difference in soil moisture levels between the two years (see Table 4.11). In 1999 the percent moisture concent of the biosolid-treated soil was greater than 123% while in 2000 it was only between 52 and 76%. The concentration-charge rule states that when soil solution becomes more dilute, di- and tri-valent cations should be preferentially adsorbed on to exchange complexes and that monovalent cations will be forced from the exchange complexes and into solution (McBride 1994). According to this model, the higher percent soil moisture content of the biosolid-treated soil in 1999 should have resulted in the following patterns: the concentrations of exchangeable monovalent cations on the exchange complex should have been lower in 1999 and higher in 2000, while the concentrations of exchangeable multi-valent cations on the exchange complex should have been higher in 1999 and lower in 2000. In fact, exchangeable K and Na were generally lower in concentration in 2000. Exchangeable Mg and Fe decreased in 2000, and exchangeable Ca and Mn were generally unchanged, while Al was unpredictable: none of the exchangeable multi-valent cations analyzed were increased in concentration in 2000.

Kraske and Fernandez (1993), conducted a study that included a surface application of primary and secondary clarifier waste rather than incorporating the clarifier waste into the soil, and the trends they observed with depth for individual exchangeable cations were not the same as those found in this study. The extent of the increase in CEC observed by Kraske and Fernandez (1993) was very slight compared to this study, likely because their amendment rates (47 to 91 Mg/ha) were lower and because their amendments did not include a nutrient-rich component. Biosolid application had a far greater effect on base saturation in their study (compared to their reference harvested plot), probably because their study areas were also far more acidic (reference plots ranged in pH from approximately 3.5 to 5.5) and had a much lower initial base saturation than those in this study.

3.4.3 Total concentration of selected macronutrients (N, P, K, Mg, and Ca)

In biosolid-treated plots, available NH_4-N concentrations were lower in 2000 for 10-20 and 20-30 cm layers of the soil profile, but slightly higher in the 0-10 cm layer than in 1999 (Figure 3.14). If we assume that NH_4-N concentrations in 2000 accurately reflected the amount of NH_4-N that could be held by soil in the 10-30 cm layer due to biological uptake, clay fixation, and interaction with other exchange surfaces, then the amounts of NH_4-N present in 1999 in the 10-30 cm layer indicated that rates of ammonification were exceeding the plant and microorganism demand for NH_4-N. In 2000, either (1) the soil conditions became less favorable for ammonification at 10-30 cm, (2) there was a decline in the amount of NH_4-N leaching from the 0-10 cm layer into the 10-30 cm, (3) there was an increased biological uptake of NH_4-N, or (4) any combination of 1-3. Regarding the second possibility, the increase in NH_4-N concentration in the 0-10 cm layer in 2000 was small, suggesting that movement of NH_4-N out of the surface of the soil profile and into the lower layers was not responsible for NH_4-N dynamics in the 10-30 cm layer. Increased biological uptake (possibility 3) is also not a suitable explanation for the behavior of NH_4-N because B+S and B plots show the same NH_4-N dynamics even though there was an increase in the density of naturally regenerating annuals and perennials in the B plots in 2000. As for conditions no longer favoring ammonification (possibility 1); although the C:N of biosolid-treated plot soil was the same in 2000 as in 1999, more labile forms of N had probably already been metabolized and the rate of mineralization in the 10-30 cm layers had slowed as a result.

While there has been evidence that nitrification in forest soils is not limited to circumstances where inputs of NH_4-N exceeds biological demand and NH_4-N fixation (Van Miegroet and

Johnson 1993), it seems reasonable to assume that biosolid application plots in this study added amounts of N that were in excess of biological requirements and that, at least in part, NO_3-N levels represent the extent to which biological requirements were exceeded. From this perspective, lower NO_3-N concentrations on biosolid-treated plots in 2000 lend support to the conclusion that soil conditions had become less favorable to mineralization as discussed above regarding NH_4-N concentrations.

Interestingly, NO_3-N was higher for B+S than B. Following the conventional assumption that NO_3-N production only occurs when NH_4-N availability exceeds biological demand (Tamm 1991), one would expect that that the higher density of grasses on B+S plots would take-up larger amounts of NH_4-N and subsequently NO_3-N concentrations would be reduced. The assumption that NO_3-N production only occurs when NH_4-N exceeds biological demand would also predict that B should have a lower overall nitrogen demand since the density of naturally seeded-in species was less than that of grasses, and therefore more NH_4-N would remain in the system for transformation to NO_3-N. In this study the reverse was true, however. Rhizosphere soils have been shown to have microbial populations much larger than those of the total soil (Paul and Clark 1996). Perhaps the higher density of grasses in B+S produced a more active rhizosphere than seen in B and the rhizosphere stimulated mineralization processes to such an extent that even though demand for N was higher in B+S than B, the mobilization of N exceeded uptake.

In a study using fertilization and seeding of legumes and grasses to reclaim a logging road, Carr (1987b) found an increase in total N from 0.016 %N to 0.31 %N after 5 years. The same report also contained information on a landing reclamation trial where tillage, fertilization, and seeding with legumes increased total N from 0.038 to 0.052 %N. Tillage alone did not produce an increase in %N of S+T or T plots compared to CP for this study (data presented as C:N).

Total N on winter- and summer-constructed landing areas studied by Carr (1987a) was 0.060 and 0.078 %N, respectively. Off-landing areas for those winter- and summer-constructed landings had 0.037 and 0.053 %N, respectively. In the present study, %N for CP at 0-10 cm was 0.060 and 0.052 at 0-10 cm, for 1999 and 2000, respectively. Total N of the OL in this study ranged from 0.099 to 0.131 %N for 2000 and 1999, respectively, at 0-10 cm. Thus, when compared to Carr (1987a), the total N observed in this study was lower for landing plots and higher for off-landing plots. This indicates that the loss of N from landing construction in the present study was greater than that for the landing areas studied by Carr (1987a). However, differences between the landings and off-landing plots were statistically significant for Carr (1987a) but not significant in the present study for the 0-10 and 10-20 cm soil layers ($p = 0.403$ and 1.000, respectively; Tables 3.11 and 3.12).

In a study that investigated the impacts of anaerobically digested municipal sludge disked into soil to a depth of 30 cm, Harrison et al. (1994) found that total P was retained in the surface soil layers 15 years after application. Long-term retention of P in the surface soil layers of the landings studied herein may also occur: the concentration of P was higher in 2000 than 1999 for 0-10 cm. It is possible that the grasses and naturally seeded in species mined lower soil layers for P and deposited it on surface layers with their senescence in

Autumn. Unfortunately, comparisons with Harrison et al. (1994) in order to confirm this hypothesis cannot be made because Harrison et al. (1994) did not present a year-by-year analysis.

Carr (1987a) found significant decreases in total P in the 0-4 cm soil layer as a result of landing construction, as did Carr (1988) when comparing soil collected to a depth of 20 cm from landing areas and off-landing controls. In the present study, total P was higher for CP than OL, but the difference was not significant.

Total K concentration in all plots and depths (except biosolid-treated plots 0-10 cm depth) increased between 1999 and 2000. Statistically, the difference between years was significant. In biosolid-treated plots, the increase of total K in 10-30 cm segments could be explained by leaching of K from the 0-10 cm layer into the 10-30 cm layer, however this explanation is not satisfactory for the other study plots. Only atmospheric inputs could be so uniform but atmospheric inputs are not a significant source of K (Brady and Weil 1999).

The lack of statistical significance in the majority of planned and post-hoc comparisons between treatments for K is understandable given that the only readily observable trend in total K concentrations (besides an overall increase between 1999 and 2000) was that biosolid-treated plots had a somewhat lower total K than other study plots. B+S also tended to have lower total K than B, however this difference was evidently not of sufficient magnitude to be detectable with the sample size available for this study. Harrison et al.

(1994) also found a slight decrease in total K in the surface soil layers with biosolid application, however they did not state whether this difference was significant.

In the studies by Carr (1987a and 1988), K concentrations decreased with landing construction but the decrease was not found to be significant. These results are reversed from that of the present study where total K was higher (but not significantly higher) for CP than OL.

In contrast to Harrison et al. (1994) who found a slight increase in total Mg with biosolid application, the present study had a slight decrease in total Mg with biosolid application (subjective interpretation, not statistically analyzed). Harrison et al. (1994) used an application rate of 500 Mg/ha, which could account for the fact that their study found an increase in total Mg while the present did not, even though the biosolids used by Harrison et al. (1994) had less Mg (350 μg Mg/g) than the biosolids used in the present study (875 μg Mg/g or more, Table 3.4).

Similar to the present study, Harrison et al. (1994) observed an increase in total Ca with biosolid application. The biosolids used by Harrison et al. (1994) contained less Ca than those used in the present study but their application rate was higher.

3.4.4 Total concentration of selected micronutrients (Cu, Zn, Fe, and Mn) and other elements (Na, Al, Ni, Cr, and Cd)

In all plots, Zn, Fe, Mn, Na, and Al had higher total concentrations in 2000 than in 1999. Total Ni, Cr, and Cd were higher in 1999. Cu concentration was higher in the 0-10 cm layer and lower in the 10-30 cm soil layers in 2000 than in 1999. Changes in Cu, Mn, Na, Ni, Cr, and Cd were large enough to arouse speculation about their ecological significance. The difference between years in the concentration of the elements was significant (although verifying this violated statistical conventions); hence, although the results are unusual, they are legitimate. For biosolid-treated plots, one could suggest that these changes were caused by the differences in the relative composition of the soil as decomposition proceeds, however this suggestion does not explain why all study plots, not just biosolid-treated ones, had similar changes. On all plots, the increase in the mass of Zn, Fe, Mn, Na, and Al in 2000 was disproportionate to the decreases in Ni, Cr, and Cd: the increases in Zn, Fe, Mn, Na, and Al were too large to have been a relative change in the elemental composition of a gram of soil caused by the decreases in Ni, Cr, and Cd.

Total Cr of biosolid-treated areas decreased in 2000 in the 0-10 cm portion of the soil profile but increased somewhat in the 10-20 and 20-30 cm portions (subjective comparison, not statistically verified). Since anion sorption is principally on mineral surfaces (McBride 1994), the very high amount of organic matter added by tilling 155 Mg/ha of primary clarifier waste and 70 Mg/ha of municipal biosolids into the soil may represent the creation of a soil which will have a very low capacity for immobilizing anions in the future.

3.6 Conclusions

Means for pH_{CaCl2}, ECEC, C:N, and total Na, Ca, and P of biosolid-treated plots were significantly different from tillage-treated and control plots. Soil properties of tillage-treated plots more resembled those of OL and CP than did biosolid-treated plots as S+T, T, CP, and OL were often not found to be significantly different from each other. While biosolid application has not come close to replicating the ecosystem of the rest of the cut block according to the measures used in this study, hopefully the nutrients added with organic matter amendment have given the landing plots the capacity to function as part of that ecosystem given time. The nutrients added were in excess of what was present off-landing and it remains for further study to evaluate whether this excess addition was required for jump-starting the biological processes of the area, or if more modest additions would have been sufficient. The significant decrease in ECEC in 2000 could either represent the system flushing itself of excess elements, or a loss which may occur in all reclamation trials no matter how low the biosolid application rate is, and therefore is a loss which will have to be taken into account when application rates are calculated.

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Table 3.1a Means (standard errors) of selected properties from pre-treatment soil samples taken in August 1998 at Clear Lake sites. Sample size was 12.

Soil Property	Depth (cm)	Mean (Standard Error) Landing One	Mean (Standard Error) Landing Two
pH_{H20}	0-10	6.26(0.075)	6.00(0.084)
	10-20	6.75(0.055)	6.06(0.110)
	20-30	6.50(0.095)	6.04(0.121)
pH_{CaCl2}	0-10	5.15(0.133)	4.76(0.118)
	10-20	5.04(0.115)	4.60(0.078)
	20-30	5.00(0.092)	4.76(0.101)
Bulk Density (kg/m^3)	0-10	1.61(0.040)	1.54(0.064)
	10-20	1.69(0.066)	1.68(0.052)
	20-30	1.77(0.046)	1.52(0.084)
ECEC ($cmol_{(+)}/kg$)	0-10	11.96(0.710)	8.96(0.693)
	10-20	11.63(1.005)	8.44(0.676)
	20-30	10.77(1.490)	8.34(0.655)
Base Saturation (%)	0-10	97.38(0.384)	92.44(1.556)
	10-20	98.25(0.410)	94.32(1.386)
	20-30	95.98(2.718)	93.90(1.238)
Total N (%)	0-10	5.08×10^{-2}(0.014)	1.09×10^{-1}(0.060)
	10-20	2.46×10^{-2}(0.002)	3.40×10^{-2}(0.005)
	20-30	2.02×10^{-2}(0.002)	5.00×10^{-2}(0.007)
Total C (%)	0-10	1.76(0.554)	1.92(0.442)
	10-20	0.72(0.315)	1.09(0.217)
	20-30	0.44(0.623)	2.16(0.450)
NO_3-N (ppm)	0-10	1.93(0.248)	2.26(0.069)
	10-20	2.15(0.202)	2.15(0.061)
	20-30	1.90(0.251)	2.22(0.052)
NH_4-N (ppm)	0-10	3.33(0.805)	2.03(0.167)
	10-20	2.73(0.540)	2.48(0.410)
	20-30	3.22(0.762)	4.14(1.100)

Table 3.1b Means (standard errors) of total elemental concentrations from pre-treatment soil samples taken in August 1998 at Clear Lake sites. Sample size was 12.

Element	Depth (cm)	Mean (Standard Error) Landing One	Mean (Standard Error) Landing Two
Al (mg/g)	0-10	64.1(1.564)	57.4(2.104)
	10-20	64.3(0.927)	61.9(1.830)
	20-30	63.5(1.178)	59.3(0.800)
K (mg/g)	0-10	15.9(0.320)	33.9(1.091)
	10-20	15.8(0.161)	15.2(0.442)
	20-30	15.5(0.306)	14.7(0.234)
Fe (mg/g)	0-10	33.9(1.091)	29.8(0.950)
	10-20	33.7(1.010)	31.8(1.181)
	20-30	34.5(1.417)	29.4(0.739)
Mg (mg/g)	0-10	95.2(0.201)	8.25(0.282)
	10-20	96.7(0.208)	9.33(0.390)
	20-30	100.0(0.320)	8.73(0.300)
Mn (μg/g)	0-10	666(23.82)	623(23.93)
	10-20	689(33.20)	656(32.62)
	20-30	708(38.97)	616(17.75)
Na (mg/g)	0-10	18.6(0.401)	17.8(0.664)
	10-20	18.5(0.329)	18.9(0.401)
	20-30	18.2(0.482)	17.9(0.218)
Cu (μg/g)	0-10	51.9(3.175)	39.1(3.031)
	10-20	49.1(2.944)	42.4(3.435)
	20-30	50.7(3.666)	35.2(3.002)
P (μg/g)	0-10	973(25.52)	920(47.34)
	10-20	930(16.08)	1070(45.61)
	20-30	930(23.21)	964(45.90)
Ca (mg/g)	0-10	14.2(0.372)	13.8(0.502)
	10-20	14.5(0.407)	14.8(0.309)
	20-30	14.3(0.419)	13.6(0.270)
Cr (μg/g)	0-10	107(3.695)	97.6(4.099)
	10-20	109(4.705)	112(4.994)
	20-30	105(3.753)	103(6.207)

Element	Depth (cm)	Mean (Standard Error) Landing One	Mean (Standard Error) Landing Two
Cd (μg/g)	0-10	11.5(0.984)	9.25(1.634)
	10-20	11.1(0.479)	10.6(0.756)
	20-30	11.2(0.725)	9.0(1.770)
Ni (μg/g)	0-10	79.5(3.608)	69.2(3.810)
	10-20	79.9(2.122)	78.1(3.262)
	20-30	82.6(3.406)	66.5(5.225)
Zn (μg/g)	0-10	90.3(1.622)	88.7(3.897)
	10-20	91.6(3.810)	99.1(7.823)
	20-30	86.0(3.175)	84.3(4.401)

Table 3.2 Soil profile description from cutover area adjacent to Landing 1 at Clear Lake sites.

Horizon	Depth (cm)	Description
Aej	0-3	Grayish brown (10YR 5/2 m); sandy clay loam; weak, fine, angular blocky; very friable; few, fine, vertical, inped and exped roots; abrupt, broken boundary; 1 to 3 cm; very strongly acid.
Bm	3-7	Brown (7.5YR 5/2 m); sandy clay loam; moderate, fine, angular blocky; very friable; plentiful, very fine, vertical and oblique exped roots, few, fine, horizontal, exped roots; 5% stones; abrupt, smooth boundary; 4 to 5 cm; very strongly acid.
Btj	7-17	Olive brown (2.5Y 4/4 m); sandy clay; weak, medium, platy breaking into moderate, fine, angular blocky; friable; few, fine, vertical, exped roots, few, medium, horizontal, exped roots; 25% stones; broken, clear boundary; 4 to 12 cm; very strongly acid.
Bmgj	17+	Olive gray (5Y 4/2 m), brown (7.5YR 5/2); sandy loam; weak, medium to coarse, sub-angular blocky; friable; dark yellowish brown (10 YR 4/6) common, medium, irregular, mottles; few, fine, oblique, exped roots, few, coarse, horizontal, exped roots; 25% stones; very strongly acid.

Total pit depth was 90 cm. Vegetation surrounding the pit included raspberry, holly, strawberry, fire weed, wild rose, white sweet clover, thistle, narrow-leaf hawkweed, spreading pod rockcress, timothy, and Queen Anne's lace. No litter layer was present, likely due to disturbance by logging activity.

Table 3.3 Soil profile description from cutover area adjacent to Landing 2 at Clear Lake sites.

Horizon	Depth (cm)	Description
L	5-0	Decomposing slash. 3-5 cm.
Aej	0-13	Dark grayish brown (10YR 4/2 m), grayish brown (2.5Y 5/2); sandy clay loam; weak, coarse, platy breaking into moderate, medium, angular blocky; friable; few, medium, horizontal, exped roots; 10% stones; abrupt, smooth boundary; 10-15 cm thick; very strongly acid.
AB	13-28	Light brownish gray (2.5Y 6/2 m); sandy clay; yellowish red (5YR 4/6) common, medium, mottles; moderate, medium, sub-angular blocky; very friable; plentiful, medium, horizontal, exped roots; 25% stones; gradual, wavy boundary; 12-18 cm thick; very strongly acid.
Bmgj	28+	Brown (7.5YR 5/2 m); sandy clay; yellowish red (5YR 4/6) many, coarse, mottles; moderate, medium, angular blocky; friable; no roots;30% stones; very strongly acid.

Total pit depth was 80cm. Vegetation surrounding the pit was sparse compared to the first profile and included raspberry, fire weed, alsike clover, narrow-leaf hawkweed, and fox tail.

Table 3.4 Properties of land stored primary clarifier waste and municipal biosolids used in the Clear Lake trials. Data is taken from Tables. 2, 3, and 4 of Van Ham (1998). Units are μg/g, unless otherwise stated. ~

	Land stored Primary Clarifier Waste		Municipal Biosolids
Property	Physical and fertility analysis	Total trace element analysis	Material characterization
pH	8.6	n.a.†	n.a.
%C**	39	n.a.	47
%N***	0.08	n.a.	4.28
NH_4-N	<13	n.a.	n.a.
NO_3-N	22	n.a.	n.a.
Al	3858	3450	30800
Na	375	387	838
P	43	1030	2.38 (%)
K	175		
Ca	42500	9900	45500
Mg	875	2660	4640
Cu	8.3	12	2650
Zn	16	43	902
Fe	800	6350	11500
Mn	98	170	1530
Cd	n.a.	BDL*	5
Cr	n.a.	19	50
Ni	n.a.	13	28
Pb	n.a.	BDL	124
Hg	n.a.	0.02	4.6
Mo	n.a.	BDL	14
Sn	n.a.	BDL	54

~ Consent was received from the Ministry of Environment, Lands and Parks for the application of these biosolids at a rate of 70 Mg/ha for municipal biosolids and 155 Mg/ha of clarifier waste to the Clear Lake landing reclamation trials under Permit #146 of the City of Prince George (Van Ham 1998).

† n.a. = not applicable

* BDL = below detection limits

** Total organic C (%)

*** Total Kjeltec N (%)

Table 3.5 Reagent amounts and concentrations used in microwave acid digestion of soil samples.

Reagent	Reagent Concentration	Amount of Reagent Used
H_2O_2	37%	2 ml
HCl	37%	1 ml
HNO_3	38%	4 ml
HF	48%	7 ml
Boric Acid	4.5%	4.5 g

Table 3.6 Duration and power sequence for the microwave program used in microwave mixed acid digestion.

Time (min)	Power (W)
2	250
2	0
6	250
5	400
5	600
10	0

Table 3.7 MANOVA table using Pillai's Trace to evaluate effects of landing reclamation on soil properties of Clear Lake trials based on the variables pH_{H2O}, log CEC ($cmol_+$/kg), total Na (mg/g), recip. total Ca (mg/g), log total P (µg/g), total K (mg/g), and log C:N. $\alpha = 0.05^*$.

Source of variation	Hypothesis df	Error df	Pillai's value	$F_{observed}$	Eta squared	Significance
Soil Depth 0-10 cm						
Year	7	34	0.72	12.71	0.723	<0.001
Treatment	21	108	1.41	4.60	0.472	<0.001
Year x Treatment	21	108	0.87	2.10	0.290	0.007
Soil Depth 10-20 cm						
Year	7	34	0.79	18.68	0.794	<0.001
Treatment	21	108	1.33	4.07	0.442	<0.001
Year x Treatment	21	108	0.48	0.99	0.161	0.485
Soil Depth 20-30 cm						
Year	7	34	0.65	9.11	0.652	<0.001
Treatment	21	108	1.34	4.18	0.448	<0.001
Year x Treatment	21	108	0.84	2.01	0.189	0.011

* In each year, sample size was six for experimental plots, three for reference plots.

Table 3.8 ANOVA table for between-subjects effects in soil properties in the 0-10 cm layer of Clear Lake trials. $\alpha = 0.00731$. See Table 3.7 for sample sizes.

Source of Variation	df	SS (Type III)	MS	$F_{observed}$	Eta squared	p-Value
Year						
pH_{CaCl2}	1	0.53	0.53	4.94	0.110	0.032
log ECEC ($cmol_+/kg$)	1	7.83×10^{-2}	7.83×10^{-2}	6.19	0.134	0.017
Na^* (mg/g)	1	7.18×10^{7}	7.18×10^{7}	4.79	0.107	0.035
recip. Ca^* (mg/g)	1	0.00	0.00	0.00	0.000	1.000
log P^* (μg/g)	1	0.19	0.19	7.06	0.150	0.011
K^* (mg/g)	1	1.52×10^{8}	1.52×10^{8}	34.89	0.466	<0.001
log C:N	1	7.52×10^{-4}	7.52×10^{-4}	0.03	0.001	0.857
Treatment						
pH_{CaCl2}	3	20.05	6.68	62.86	0.825	<0.001
log ECEC ($cmol_+/kg$)	3	3.07	1.022	80.79	0.858	<0.001
Na^* (mg/g)	3	7.48×10^{8}	2.49×10^{8}	16.66	0.555	<0.001
recip. Ca^* (mg/g)	3	7.06×10^{-9}	2.35×10^{-9}	28.22	0.679	<0.001
log P^* (μg/g)	3	4.04	1.35	51.25	0.794	<0.001
K^* (mg/g)	3	2.05×10^{8}	6.82×10^{7}	15.64	0.540	<0.001
log C:N	3	1.74	0.58	25.49	0.657	<0.001
Year x Treatment						
pH_{CaCl2}	3	0.14	4.52×10^{-2}	0.43	0.031	0.736
log ECEC ($cmol_+/kg$)	3	3.10×10^{-2}	1.03×10^{-2}	0.82	0.058	0.492
Na^* (mg/g)	3	1.88×10^{8}	6.25×10^{7}	4.17	0.238	0.012
recip. Ca^* (mg/g)	3	1.98×10^{-10}	6.61×19^{-11}	0.79	0.056	0.505
log P^* (μg/g)	3	0.44	0.15	5.60	0.296	0.003
K^* (mg/g)	3	5.42×10^{7}	1.81×10^{7}	4.14	0.237	0.012
log C:N	3	6.27×10^{-3}	2.09×10^{-3}	0.09	0.007	0.964
Error						
pH_{CaCl2}	40	4.25	0.11			
log ECEC ($cmol_+/kg$)	40	0.51	1.27×10^{-2}			
Na^* (mg/g)	40	5.99×10^{8}	1.50×10^{7}			
recip. Ca^* (mg/g)	40	3.34×10^{-9}	8.34×10^{-11}			
log P^* (μg/g)	40	1.05	2.63×10^{-2}			
K^* (mg/g)	40	1.74×10^{8}	4.36×10^{6}			
log C:N	40	0.91	2.28×10^{-2}			

* These values are total concentration of the given element, as extracted by mixed acid microwave digestion.

Table 3.9 ANOVA table for between-subjects effects in soil properties in the 10-20 cm layer of Clear Lake trials. $\alpha = 0.00731$. See Table 3.7 for sample sizes.

Source of Variation	df	SS (Type III)	MS	$F_{observed}$	Eta squared	p-Value
Year						
pH_{CaCl2}	1	5.22×10^{-2}	5.22×10^{-2}	0.47	0.012	0.498
log ECEC ($cmol_+/kg$)	1	0.14	0.14	7.70	0.161	0.008
Na^* (mg/g)	1	1.93×10^{8}	1.93×10^{8}	22.62	0.361	<0.001
recip. Ca^* (mg/g)	1	5.30×10^{-11}	5.30×10^{-11}	0.96	0.023	0.334
log P^* (µg/g)	1	3.05×10^{-2}	3.05×10^{-2}	1.48	0.036	0.231
K^* (mg/g)	1	2.58×10^{8}	2.58×10^{8}	114.64	0.741	<0.001
log C:N	1	3.07×10^{-4}	3.07×10^{-4}	0.01	<0.001	0.906
Treatment						
pH_{CaCl2}	3	12.72	4.24	37.96	0.740	<0.001
log ECEC ($cmol_+/kg$)	3	1.31	0.44	23.84	0.641	<0.001
Na^* (mg/g)	3	1.37×10^{8}	4.55×10^{7}	5.33	0.286	0.003
recip. Ca^* (mg/g)	3	2.03×10^{-9}	6.78×10^{10}	12.23	0.478	<0.001
log P^* (µg/g)	3	1.26	0.42	20.33	0.604	<0.001
K^* (mg/g)	3	7.63×10^{7}	2.54×10^{7}	11.30	0.459	<0.001
log C:N	3	0.59	0.20	9.10	0.406	<0.001
Error						
pH_{CaCl2}	40	4.47	0.11			
log ECEC ($cmol_+/kg$)	40	0.74	1.84×10^{-2}			
Na^* (mg/g)	40	3.41×10^{8}	8.53×10^{6}			
recip. Ca^* (mg/g)	40	2.22×10^{-9}	5.54×10^{-11}			
log P^* (µg/g)	40	0.83	2.06×10^{-2}			
K^* (mg/g)	40	9.01×10^{7}	2.25×10^{6}			
log C:N	40	0.87	2.17×10^{-2}			

* These values are total concentration of the given element, as extracted by mixed acid microwave digestion.

Table 3.10 ANOVA table for between-subjects effects in soil properties in the 20-30 cm layer of Clear Lake trials. $\alpha = 0.00731$. See Table 3.7 for sample sizes.

Source of Variation	df	SS (Type III)	MS	$F_{observed}$	Eta squared	p-Value
Year						
pH_{CaCl2}	1	2.43×10^{-2}	2.43×10^{-2}	0.24	0.006	0.628
log ECEC ($cmol_+$/kg)	1	0.26	0.26	10.21	0.200	0.003
Na^* (mg/g)	1	1.80×10^{8}	1.80×10^{8}	23.87	0.374	<0.001
recip. Ca^* (mg/g)	1	4.45×10^{-12}	4.45×10^{-12}	0.07	0.002	0.797
log P^* (μg/g)	1	0.17	0.17	5.91	0.129	0.020
K^* (mg/g)	1	2.24×10^{8}	2.24×10^{8}	61.99	0.608	<0.001
log C:N	1	6.51×10^{-2}	6.51×10^{-2}	4.29	0.097	0.045
Treatment						
pH_{CaCl2}	3	10.76	3.59	35.21	0.725	<0.001
log ECEC ($cmol_+$/kg)	3	0.75	0.25	9.66	0.420	<0.001
Na^* (mg/g)	3	7.64×10^{6}	2.54×10^{6}	0.34	0.025	0.799
recip. Ca^* (mg/g)	3	1.59×10^{-9}	5.29×10^{-10}	7.99	0.375	<0.001
log P^* (μg/g)	3	0.75	0.25	8.88	0.400	<0.001
K^* (mg/g)	3	7.94×10^{6}	2.65×10^{6}	0.73	0.052	0.538
log C:N	3	0.40	0.13	8.76	0.397	<0.001
Year x Treatment						
pH_{CaCl2}	3	0.52	0.17	1.71	0.114	0.180
log ECEC ($cmol_+$/kg)	3	0.13	4.31×10^{-2}	1.66	0.111	0.192
Na^* (mg/g)	3	4.63×10^{7}	1.54×10^{7}	2.04	0.133	0.123
recip. Ca^* (mg/g)	3	1.43×10^{-10}	4.77×10^{-11}	0.72	0.051	0.545
log P^* (μg/g)	3	0.18	6.01×10^{-2}	2.14	0.138	0.110
K^* (mg/g)	3	1.30×10^{7}	4.34×10^{6}	1.20	0.083	0.322
log C:N	3	2.44×10^{-2}	8.12×10^{-3}	0.54	0.039	0.661
Error						
pH_{CaCl2}	40	4.08	0.10			
log ECEC ($cmol_+$/kg)	40	1.04	2.60×10^{-2}			
Na^* (mg/g)	40	3.02×10^{8}	7.55×10^{6}			
recip. Ca^* (mg/g)	40	2.65×10^{-9}	6.62×10^{-11}			
log P^* (μg/g)	40	1.12	2.81×10^{-2}			
K^* (mg/g)	40	1.44×10^{8}	3.61×10^{6}			
log C:N	40	0.61	1.52×10^{-2}			

* These values are total concentration of the given element, as extracted by mixed acid microwave digestion.

Table 3.11a P-values of planned comparisons for soil properties in the 0-10 cm layer of the Clear Lake reclamation trials using Dunnett's method. $\alpha = 0.05$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable						
	pH_{CaCl2}	log ECEC (cmol+/kg)	Total Na (mg/g)	recip. Total Ca (mg/g)	log Total P (μg/g)	Total K (mg/g)	log C:N
H_1: S+T = CP	0.623	0.105	0.995	0.640	0.555	0.701	1.000
H_2: T = CP	0.560	0.012	1.000	0.594	0.235	0.879	0.640
H_3: B+S = CP	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
H_4: B = CP	<0.001	<0.001	0.013	0.003	0.002	0.182	0.003
H_5: S+T = OL	0.051	0.997	0.857	0.954	0.981	0.193	1.000
H_6: T = OL	<0.001	0.553	0.683	0.972	1.000	0.312	0.511
H_7: B+S = OL	<0.001	<0.001	0.002	<0.001	<0.001	0.025	<0.001
H_8: B = OL	<0.001	<0.001	0.167	<0.001	<0.001	0.679	0.004
H_9: CP = OL	0.011	0.299	0.793	0.409	0.403	0.869	1.000

Table 3.11b P-values of post-hoc comparisons for soil properties in the 0-10 cm layer of the Clear Lake reclamation trials using Bonferroni for log ECEC and Tamhane's T2 for all other variables. $\alpha = 0.008$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable						
	pH_{CaCl2}	log ECEC (cmol+/kg)	Total Na (mg/g)	recip. Total Ca (mg/g)	log Total P (μg/g)	Total K (mg/g)	log C:N
H_{10}: B+S = B	0.993	0.079	0.735	1.000	0.733	0.931	0.440
H_{11}: B+S = S+T	<0.001	<0.001	0.001	<0.001	<0.001	0.007	0.002
H_{12}: B+S = T	0.002	<0.001	0.001	<0.001	<0.001	0.023	<0.001
H_{13}: B = S+T	<0.001	<0.001	0.099	0.003	0.007	0.162	0.029
H_{14}: B = T	0.001	<0.001	0.062	0.002	0.003	0.398	<0.001
H_{15}: S+T = T	0.706	1.000	1.000	1.000	0.998	1.000	0.982

* Pair-wise comparisons were based on pooled data. Results from 1999 and 2000 were pooled in order to achieve a sufficient sample size for statistical analysis. See Table 3.16 for pooled means.

Table 3.12a P-values of planned comparisons for soil properties in the 10-20 cm layer of the Clear Lake reclamation trials using Dunnett's method. $\alpha = 0.05$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable						
	pH_{CaCl2}	log ECEC (cmol+/kg)	Total Na (mg/g)	recip. Total Ca (mg/g)	log Total P (µg/g)	Total K (mg/g)	log C:N
H_1: S+T = CP	0.790	0.043	0.386	0.871	1.000	0.780	0.514
H_2: T = CP	0.026	0.002	0.916	1.000	0.985	0.514	0.104
H_3: B+S = CP	<0.001	<0.001	0.002	0.009	<0.001	0.027	0.393
H_4: B = CP	<0.001	<0.001	0.141	0.033	0.005	0.503	0.897
H_5: S+T = OL	0.037	0.355	0.719	1.000	1.000	0.404	0.683
H_6: T = OL	<0.001	0.037	0.225	0.971	0.937	0.216	0.198
H_7: B+S = OL	<0.001	<0.001	0.496	0.002	<0.001	0.095	0.230
H_8: B = OL	<0.001	<0.001	0.987	0.007	0.008	0.876	0.690
H_9: CP = OL	0.354	0.764	0.119	0.960	1.000	0.977	0.998

Table 3.12b P-values of post-hoc comparisons for soil properties in the 10-20 cm layer of the Clear Lake reclamation trials using Bonferroni for log ECEC and log C:N, and Tamhane's T2 for all other variables. $\alpha = 0.008$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable						
	pH_{CaCl2}	log ECEC (cmol+/kg)	Total Na (mg/g)	recip. Total Ca (mg/g)	log Total P (µg/g)	Total K (mg/g)	log C:N
H_{10}: B+S = B	0.959	1.000	0.975	1.000	0.999	1.000	1.000
H_{11}: B+S = S+T	<0.001	<0.001	0.541	0.016	0.042	0.266	0.017
H_{12}: B+S = T	0.036	<0.001	0.103	0.087	0.017	0.212	0.001
H_{13}: B = S+T	<0.001	<0.001	1.000	0.073	0.082	0.954	0.212
H_{14}: B = T	0.002	0.001	0.994	0.291	0.018	0.896	0.013
H_{15}: S+T = T	0.806	1.000	1.000	1.000	0.998	1.000	1.000

* Pair-wise comparisons were based on pooled data. Results from 1999 and 2000 were pooled in order to achieve a sufficient sample size for statistical analysis. See Table 3.16 for pooled means.

Table 3.13a P-values of planned comparisons for soil properties in the 20-30 cm layer of the Clear Lake reclamation trials using Dunnett's method. $\alpha = 0.05$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable				
	pH_{CaCl2}	log ECEC (cmol+/kg)	recip. Total Ca (mg/g)	log Total P (µg/g)	log C:N
H_1: S+T = CP	0.999	0.775	0.176	0.437	0.687
H_2: T = CP	0.090	0.735	0.505	0.985	1.000
H_3: B+S = CP	<0.001	0.006	0.249	0.076	0.001
H_4: B = CP	<0.001	<0.001	0.999	0.440	0.071
H_5: S+T = OL	0.313	0.137	0.601	0.641	0.490
H_6: T = OL	0.003	0.122	0.970	1.000	0.087
H_7: B+S = OL	<0.001	<0.001	0.050	0.039	0.318
H_8: B = OL	<0.001	<0.001	0.963	0.276	1.000
H_9: CP = OL	0.564	0.709	0.909	0.009	0.147

Table 3.13b P-values of post-hoc comparisons for soil properties in the 20-30 cm layer of the Clear Lake reclamation trials using Bonferroni for log C:N and Tamhane's T2 for all other variables. $\alpha = 0.008$. See Table 3.7 for sample sizes.*

Planned Comparison	Variable				
	pH_{CaCl2}	log ECEC (cmol+/kg)	recip. Total Ca (mg/g)	log Total P (µg/g)	log C:N
H_{10}: B+S = B	1.000	0.999	0.651	0.999	0.880
H_{11}: B+S = S+T	<0.001	0.301	0.001	0.037	0.013
H_{12}: B+S = T	0.011	0.318	0.010	0.079	<0.001
H_{13}: B = S+T	<0.001	0.044	0.760	0.206	1.000
H_{14}: B = T	0.001	0.047	0.995	0.443	0.097
H_{15}: S+T = T	0.426	1.000	0.996	0.987	1.000

* Pair-wise comparisons were based on pooled data. Results from 1999 and 2000 were pooled in order to achieve a sufficient sample size for statistical analysis. See Table 3.16 for pooled means.

Table 3.14 Mean (standard error) of bulk density (g/cm^3) for soil samples taken at Clear Lake trials. Sample size was six for B+S, B, S+T, and T; three for OL and CP.

Depth	Plot Identification					
(cm)	B+S	B	S+T	T	OL	CP
1999						
0-10	0.41(0.031)	0.65(0.106)	1.09(0.133)	0.99(0.142)	1.12(0.218)	1.45(0.090)
10-20	0.83(0.120)	0.83(0.147)	1.28(0.219)	1.31(0.151)	1.41(0.140)	1.77(0.192)
20-30	0.77(0.150)	1.34(0.209)	1.95(0.104)	1.71(0.138)	1.53(0.179)	1.92(0.026)
2000						
0-10	0.33(0.028)	0.54(0.093)	1.07(0.118)	1.05(0.162)	0.76(0.160)	1.53(0.082)
10-20	0.90(0.263)	1.25(0.273)	1.61(0.128)	1.41(0.125)	0.96(0.086)	1.82(0.018)
20-30	1.43(0.243)	1.34(0.290)	1.93(0.110)	1.71(0.168)	1.83(0.143)	1.56(0.036)

Table 3.15 Mean and standard error of base saturation (%) of soils from Clear Lake sites. Sample size was six for B+S, B, S+T, and T; three for OL and CP.

Depth	Plot Identification					
(cm)	B+S	B	S+T	T	OL	CP
1999						
0-10	99.61(0.05)	99.63(0.10)	96.55(0.74)	95.94(1.29)	82.71(8.56)	95.86(1.88)
10-20	98.83(0.34)	99.32(0.14)	95.63(1.47)	96.97(0.88)	90.04(5.46)	95.21(1.37)
20-30	97.19(1.28)	99.05(0.16)	94.68(2.04)	96.97(0.66)	93.08(3.14)	96.56(1.21)
2000						
0-10	99.43(0.11)	99.61(0.03)	94.96(1.19)	97.09(0.99)	80.86(2.93)	97.07(0.63)
10-20	98.26(0.64)	99.32(0.12)	96.16(1.21)	98.01(0.85)	88.49(1.10)	97.46(1.00)
20-30	98.20(0.72)	99.15(0.26)	97.21(0.67)	96.32(1.30)	96.02(1.97)	97.86(1.00)

Table 3.16 Pooled means (standard error)† for 1999 and 2000 soil properties of the Clear Lake reclamation trials. See Table 3.7 for sample sizes.

Variable	Plot Identification					
and Depth	B+S	B	S+T	T	OL	CP
pH_{CaCl2}						
0-10	6.29(0.077)^{a}	6.43(0.088)^{a}	4.91(0.084)^{bc}	5.29(0.185)^{b}	4.49(0.178)^{c}	5.09(0.135)^{b}
10-20	6.04(0.131)^{ab}	6.25(0.093)^{a}	4.99(0.095)^{ce}	5.32(0.164)^{cb}	4.54(0.171)^{d}	4.84(0.099)^{de}
20-30	6.03(0.122)^{a}	6.15(0.099)^{a}	5.01(0.075)^{bc}	5.34(0.126)^{b}	4.75(0.130)^{cd}	4.98(0.130)^{bd}
ECEC ($cmol_{+}$/kg)						
0-10	41.08(3.36)^{a}	30.94(3.23)^{a}	10.42(0.64)^{bc}	11.86(0.85)^{c}	10.53(1.62)^{bc}	7.82(0.71)^{b}
10-20	27.42(5.13)^{a}	21.00(2.65)^{a}	7.82(1.49)^{bd}	11.44(0.91)^{b}	7.82(1.49)^{cd}	6.33(0.72)^{c}
20-30	17.13(2.80)^{a}	22.10(5.43)^{a}	10.15(1.11)^{ab}	10.27(1.22)^{ab}	7.20(1.64)^{b}	8.12(0.71)^{b}
Na^{*} (mg/kg)						
0-10	11.44(1.40)^{a}	15.10(1.43)^{ab}	20.44(1.06)^{bc}	20.99(1.16)^{bc}	18.95(1.41)^{bc}	21.11(1.87)^{c}
10-20	16.50(1.20)^{a}	19.05(1.60)^{ab}	19.90(1.12)^{ab}	21.10(0.98)^{ab}	18.43(0.73)^{ab}	22.08(0.77)^{b}
20-30	19.38(1.20)	20.02(1.81)	19.90(0.62)	20.51(1.11)	19.83(0.78)	22.55(1.21)
Ca^{*} (mg/kg)						
0-10	24.90(2.09)^{a}	23.29(2.18)^{a}	14.60(0.41)^{b}	14.50(0.32)^{b}	14.18(0.77)^{b}	15.84(0.81)^{b}
10-20	19.34(1.56)^{a}	18.89(1.78)^{a}	14.47(0.37)^{ab}	15.08(0.54)^{ab}	14.65(0.77)^{b}	14.99(0.22)^{b}
20-30	18.07(0.76)^{a}	16.26(1.42)^{ab}	14.04(0.35)^{b}	14.61(0.38)^{ab}	14.97(0.26)^{b}	16.02(1.06)^{ab}
P^{*} (mg/kg)						
0-10	5.61(1.63)^{a}	2.93(0.58)^{a}	0.95(0.07)^{b}	0.85(0.06)^{b}	0.85(0.06)^{b}	1.18(0.10)^{b}
10-20	2.59(0.63)^{a}	1.82(0.31)^{a}	0.95(0.08)^{ab}	0.83(0.03)^{ab}	0.93(0.06)^{b}	0.92(0.11)^{b}
20-30	1.77(0.27)^{a}	1.51(0.36)^{ab}	0.82(0.09)^{ab}	0.92(0.06)^{ab}	0.93(0.05)^{b}	1.04(0.16)^{a}

Variable and Depth	Plot Identification					
	B+S	B	S+T	T	OL	CP
K* (mg/kg)						
0-10	10.44(0.97)^{a}	12.32(0.88)^{ab}	15.43(0.69)^{b}	15.14(0.87)^{b}	13.43(1.26)^{b}	14.36(1.21)^{b}
10-20	12.35(0.90)^{a}	13.49(1.02)^{ab}	15.16(0.66)^{ab}	15.44(0.76)^{ab}	14.06(0.97)^{ab}	14.47(1.14)^{b}
20-30	14.68(1.15)	14.87(1.13)	15.76(0.65)	15.12(0.83)	14.11(0.788)	17.04(1.11)
C:N						
0-10	12.35(0.68)^{a}	16.00(1.56)^{ab}	32.07(3.93)^{bc}	36.24(2.44)^{c}	33.03(10.11)^{c}	29.42(1.82)^{c}
10-20	15.52(1.63)^{a}	17.41(1.46)^{ab}	26.77(3.64)^{ab}	29.15(2.87)^{b}	21.77(4.52)^{ab}	20.04(3.02)^{ab}
20-30	14.43(1.52)^{a}	17.74(1.33)^{ab}	22.34(2.58)^{ab}	25.41(2.59)^{b}	17.64(1.68)^{ab}	24.80(2.39)^{b}

† Means within a row with the same superscript letters were not significantly different. Means with no superscripts had no significant differences between treatments.

* These values are total concentration of the given element, as extracted by mixed acid microwave digestion.

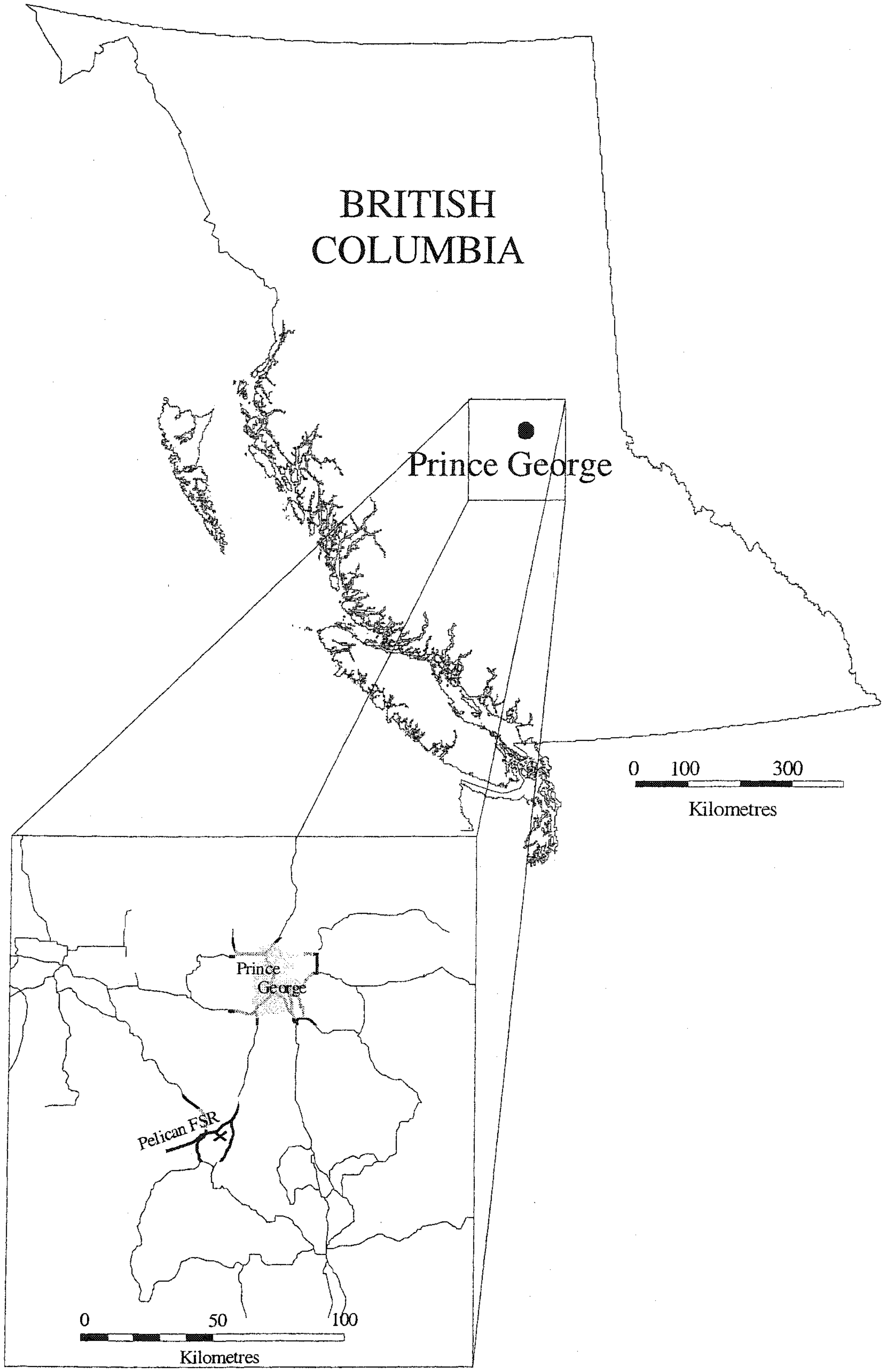


Figure 3.1 Location of Prince George in British Columbia, Canada. Inset shows approximate location of study sites relative to Prince George and major highways and local roads. Study sites were located at roughly N 53° 39' 13", W 122° 56' 49" using datum NAD 83.

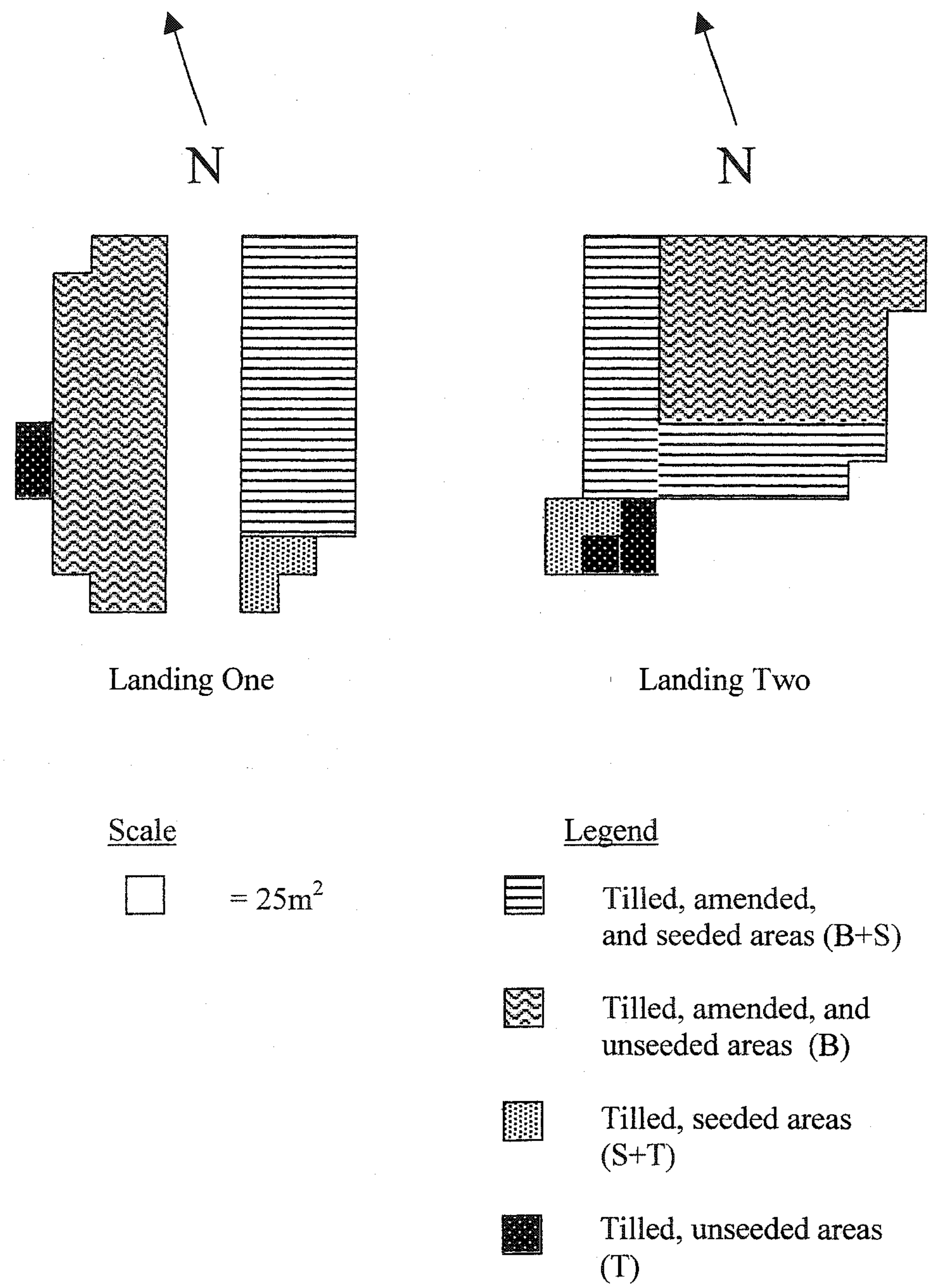
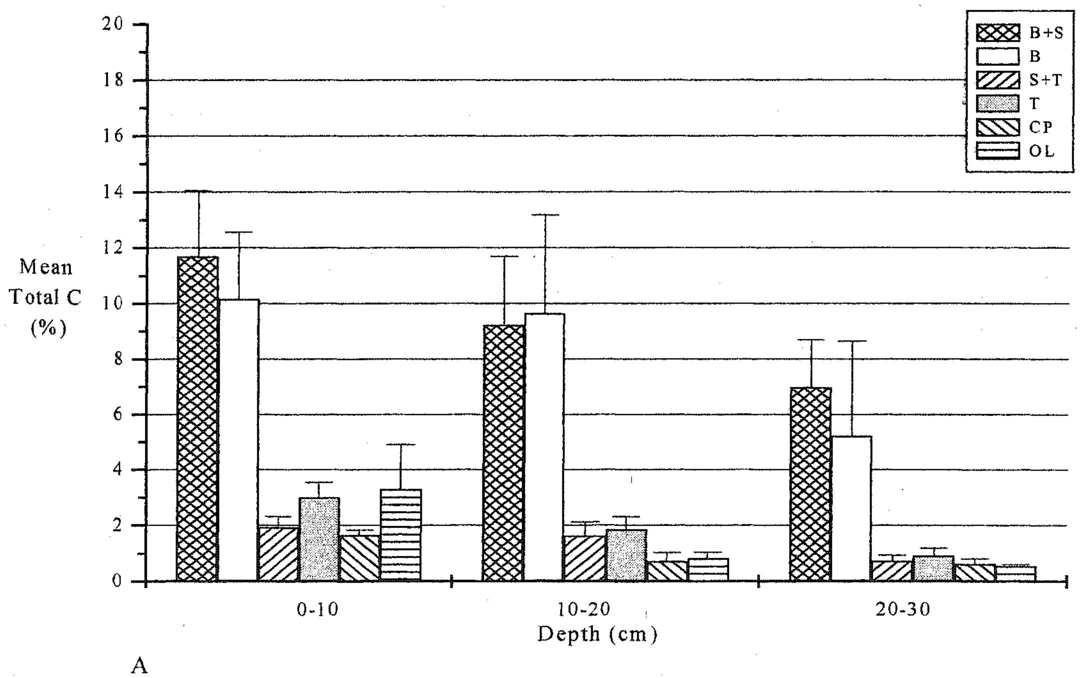


Figure 3.2 Layout of amendment application and seeding of fallow crop for landing reclamation trial.



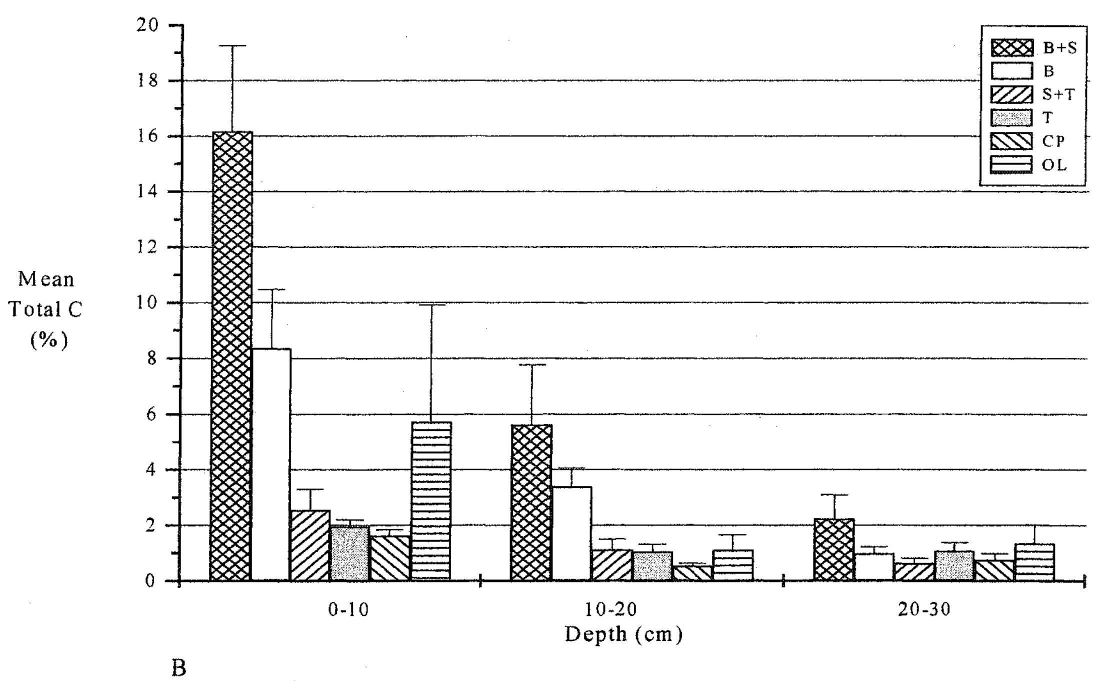
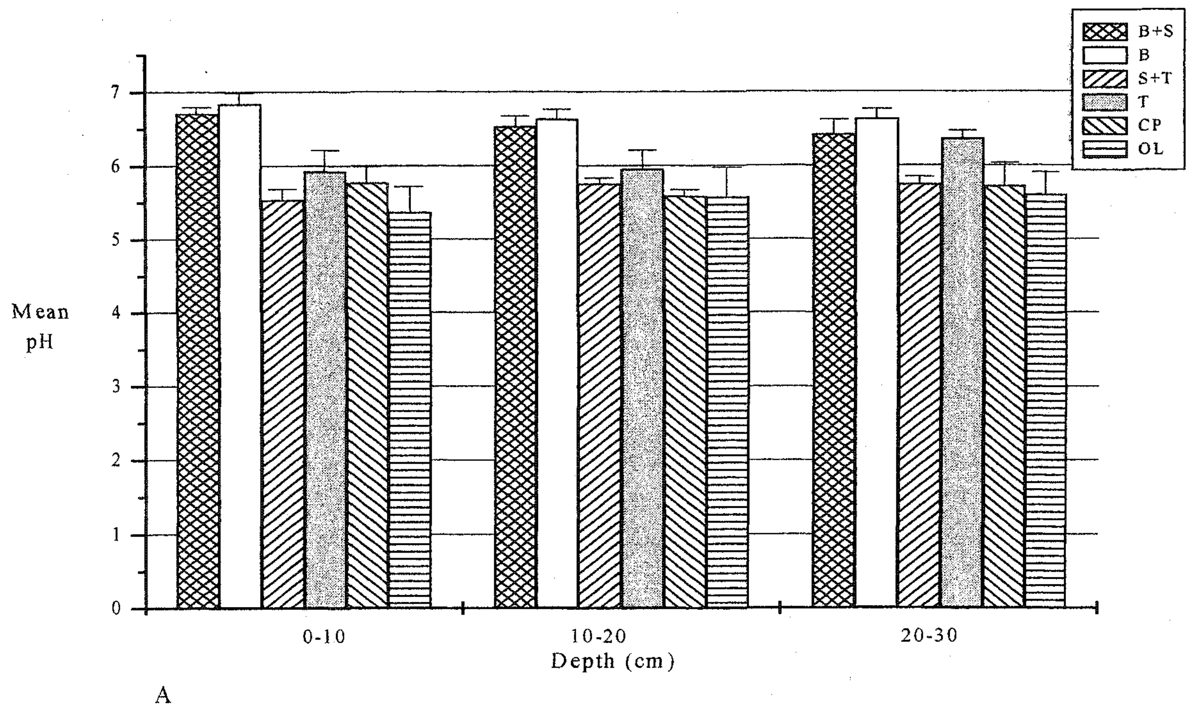


Figure 3.3 Mean total soil C for experimental and reference plots of the Clear Lake sites. Sample size for B+S, B, S+T, and T is six; for CA and OL is three. Error bars indicate standard error. Figure 3.3A - 1999, Figure 3.3B - 2000.



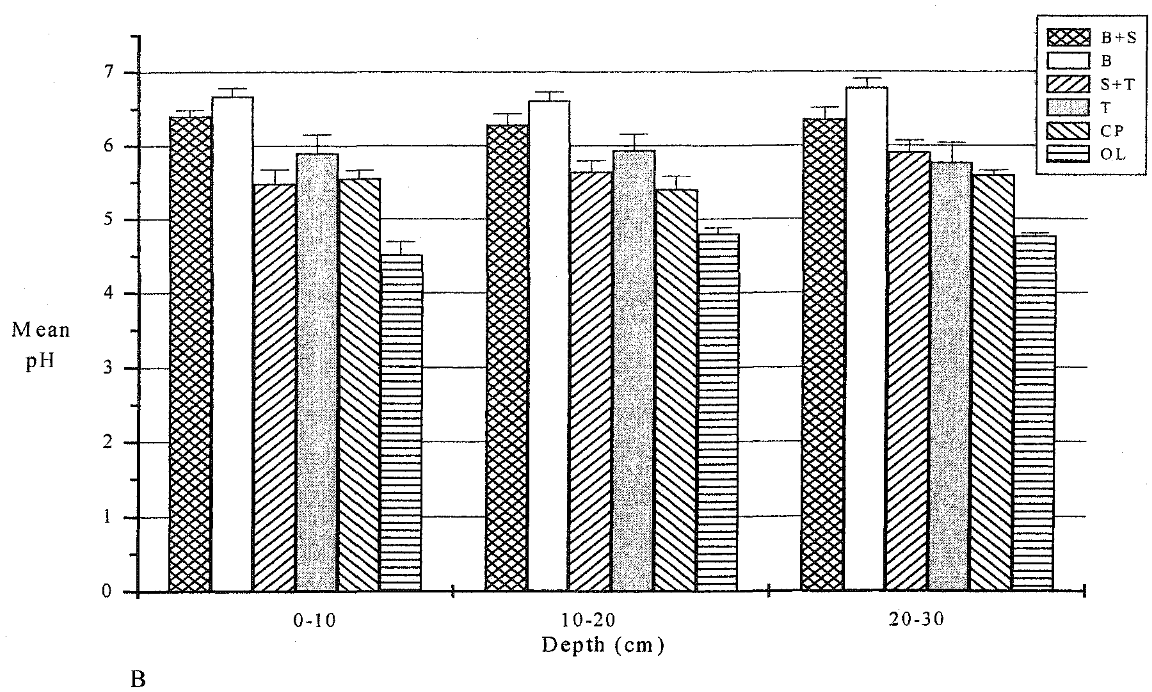
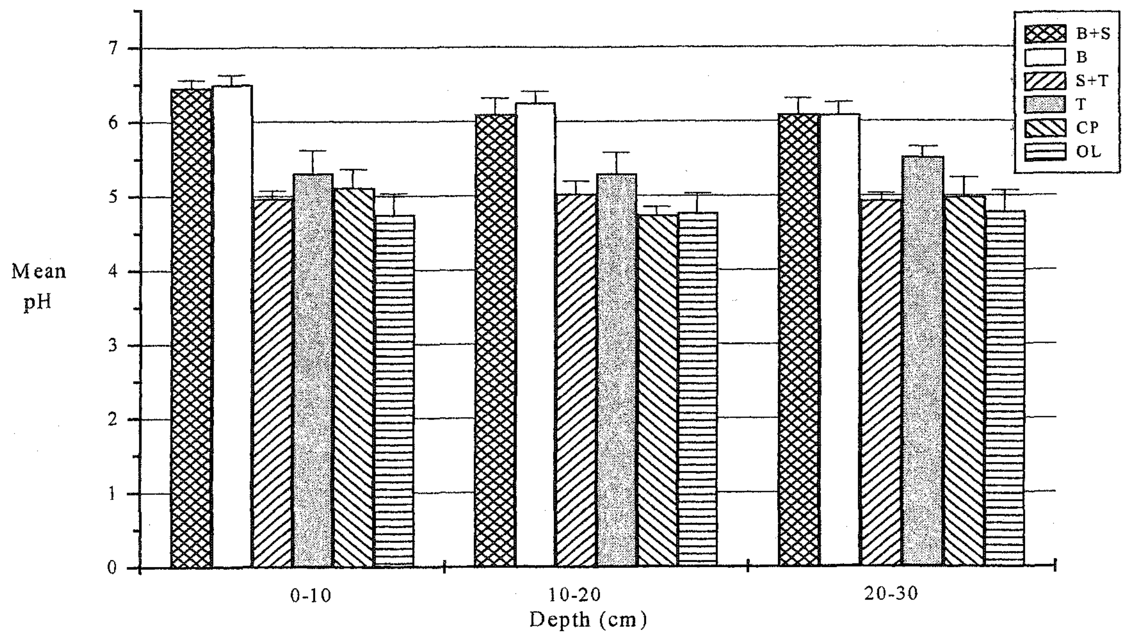
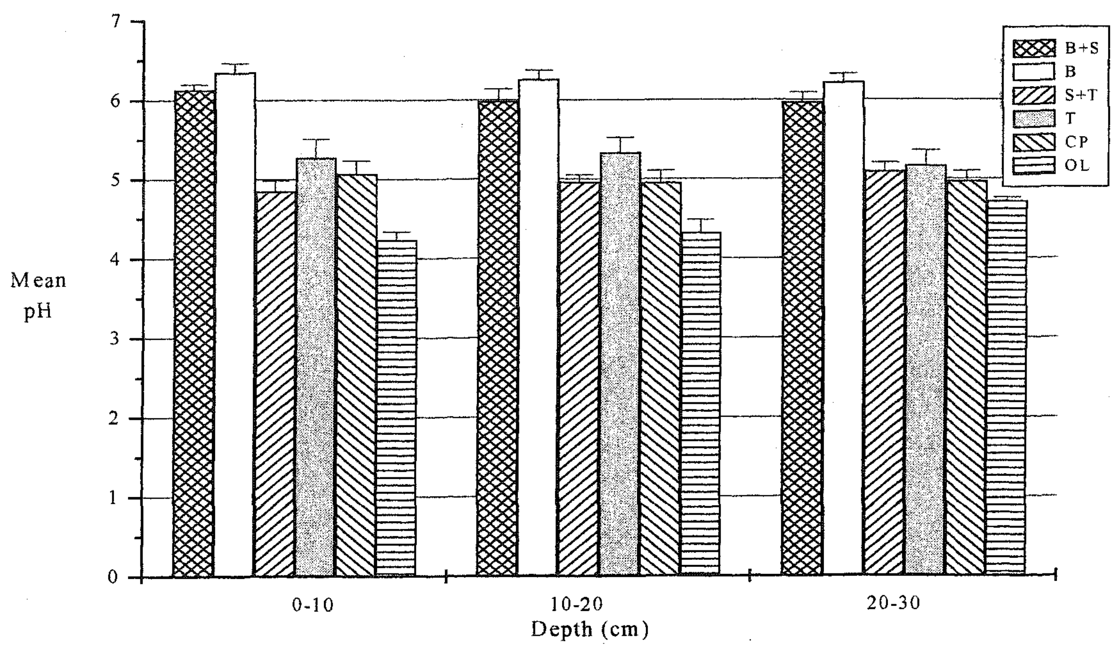


Figure 3.4 Mean soil pH_{H20} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.4A - 1999, Figure 3.4B - 2000.

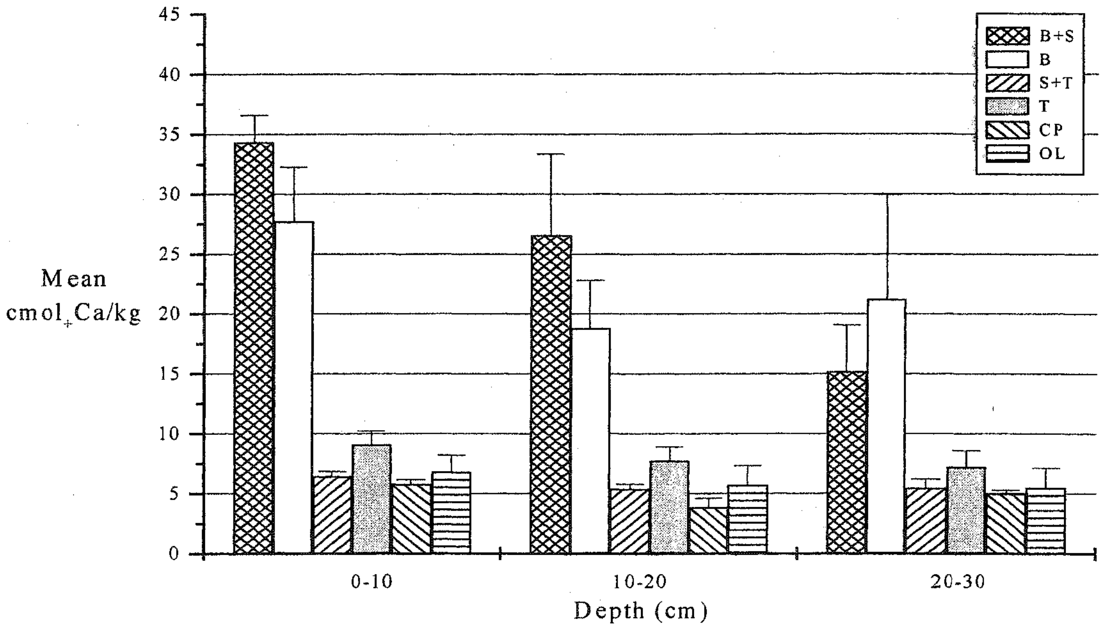


A

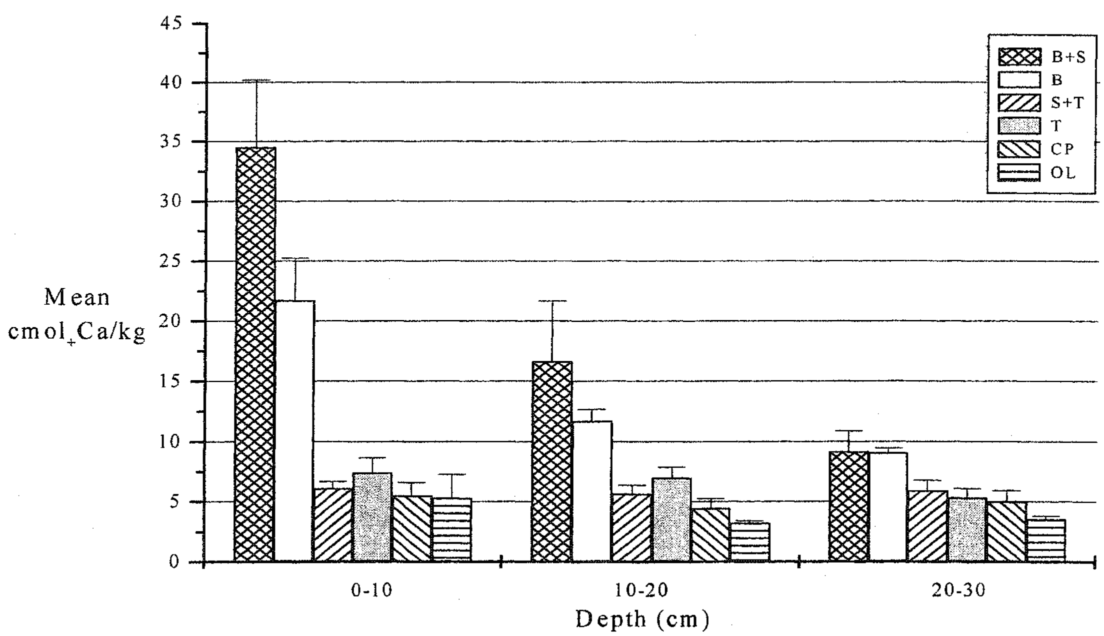


B

Figure 3.5 Mean soil pH_{CaCl2} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.5A – 1999, Figure 3.5B - 2000.

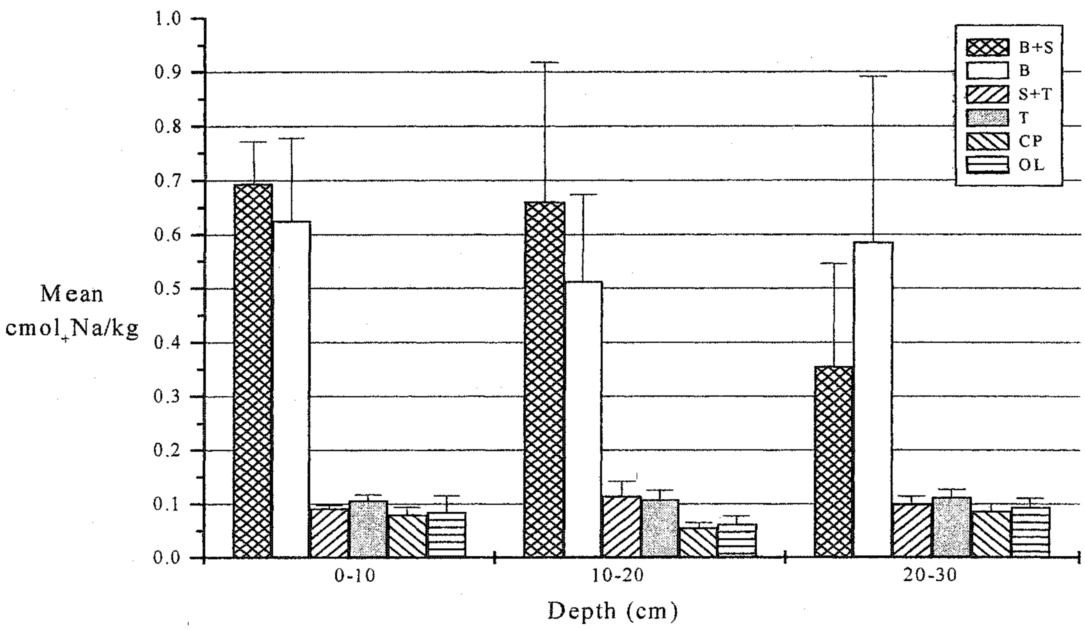


A

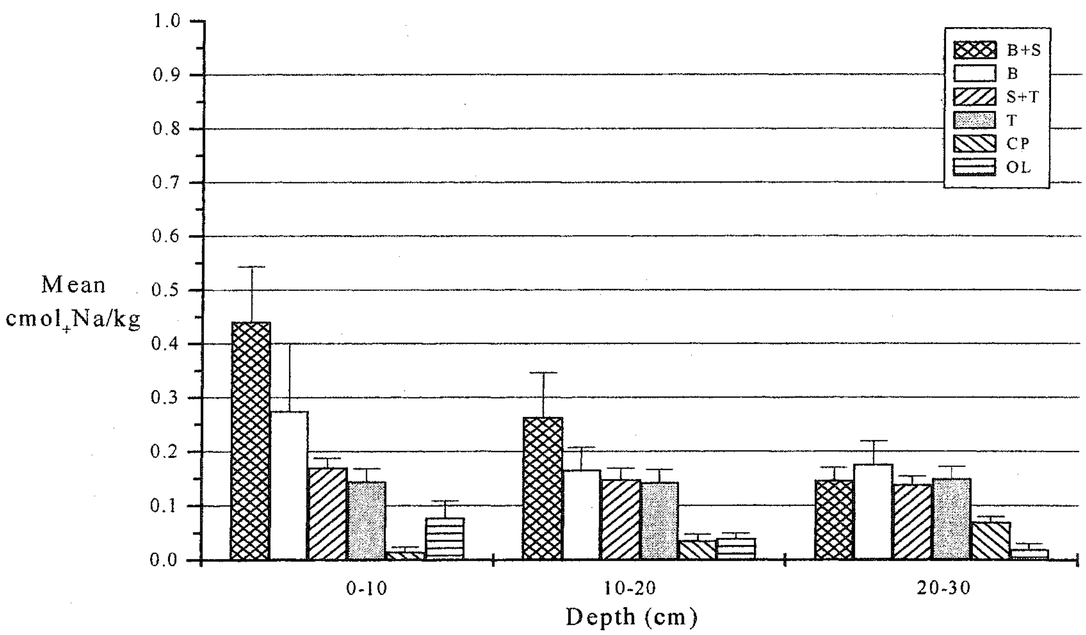


B

Figure 3.6 Mean exchangeable Ca^{2+} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure. 3.6A - 1999, Figure 3.6B - 2000.

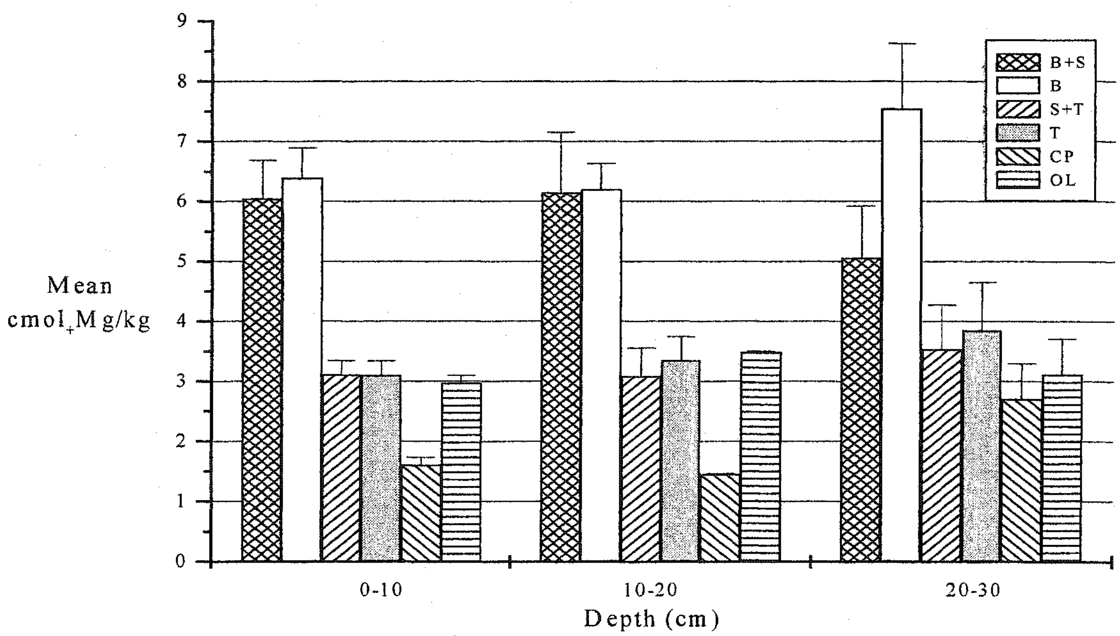


A

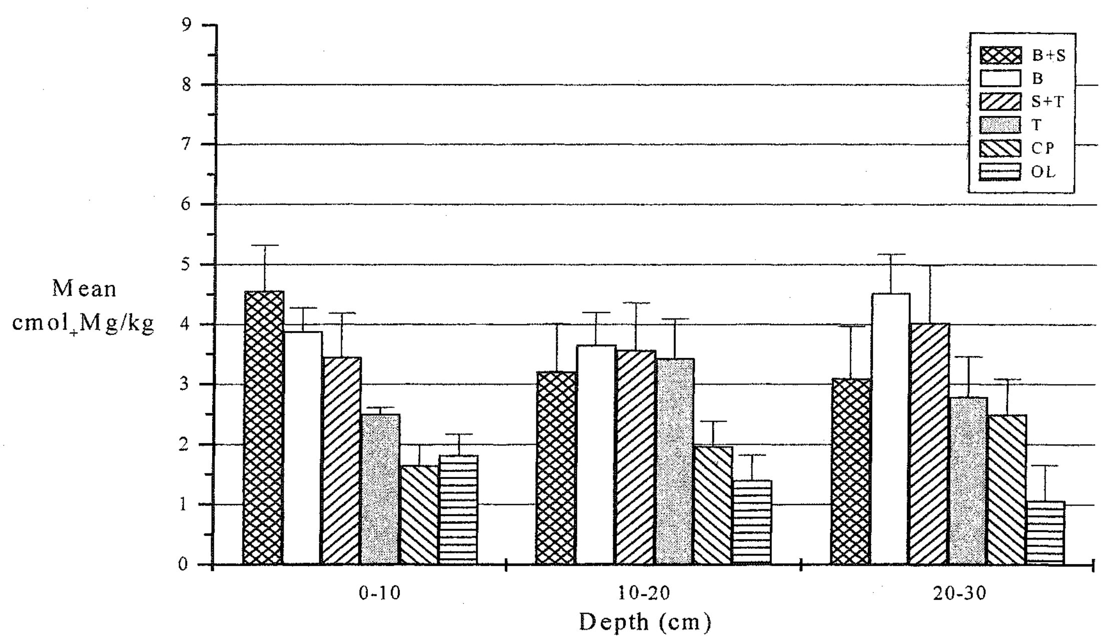


B

Figure 3.7 Mean exchangeable Na^+ for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.7A - 1999, Figure 3.7B - 2000.

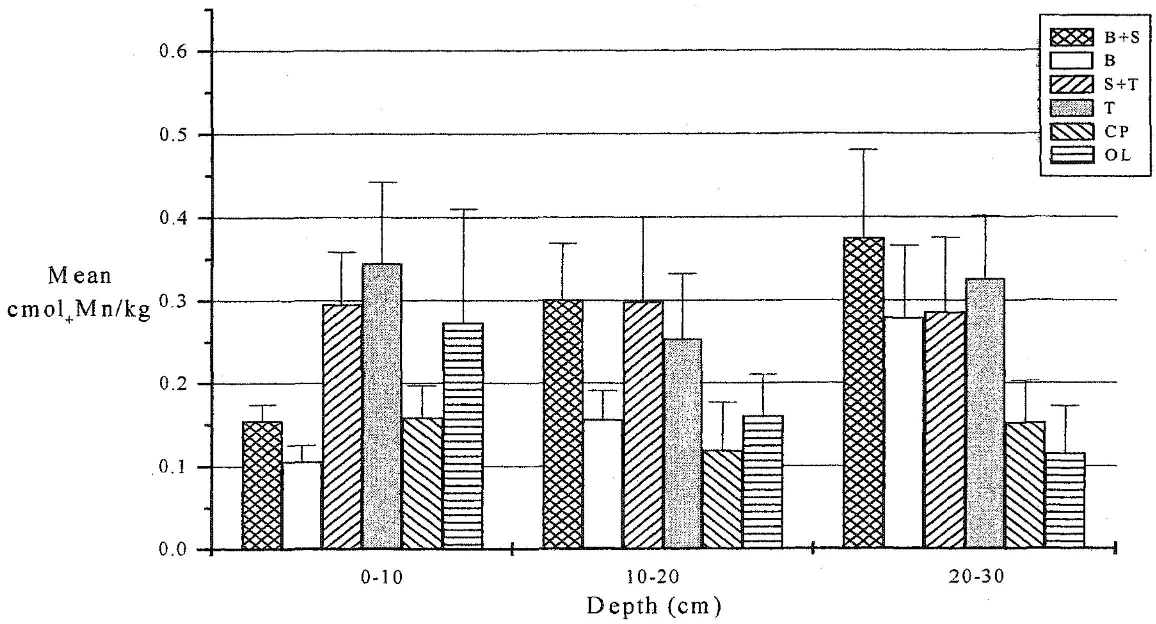


A

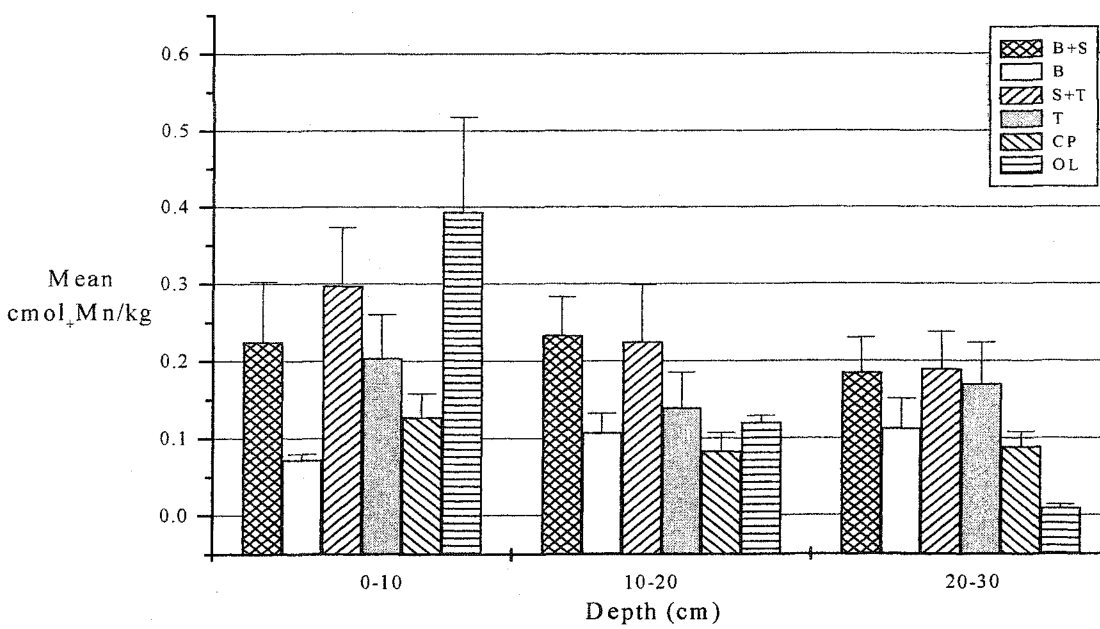


B

Figure 3.8 Mean exchangeable Mg^{2+} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.8A - 1999, Figure 3.8B - 2000.

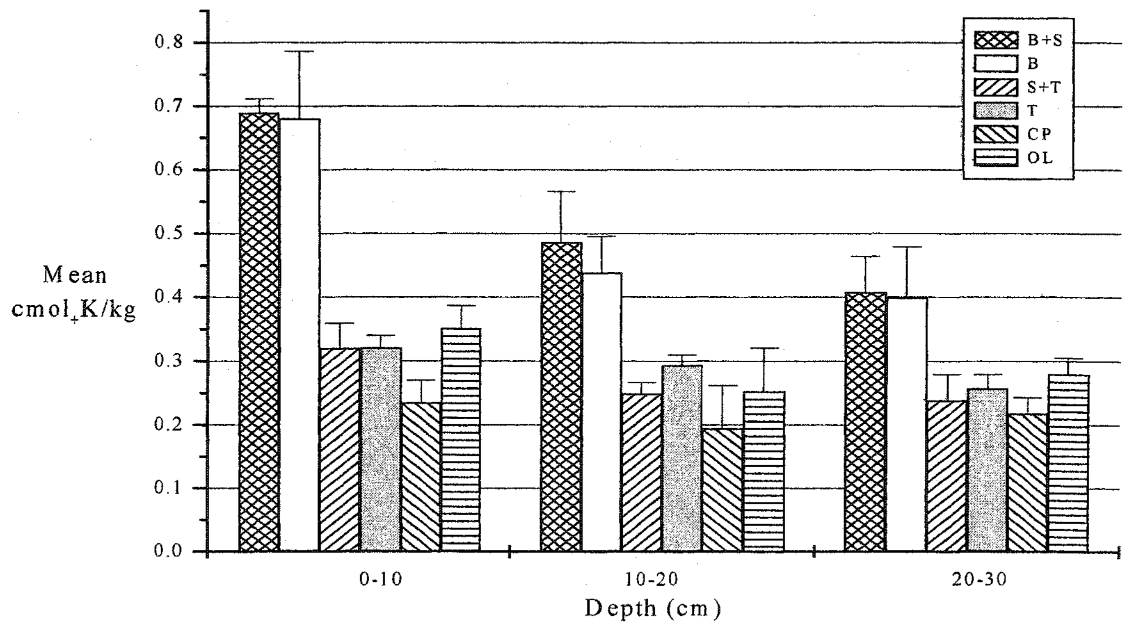


A

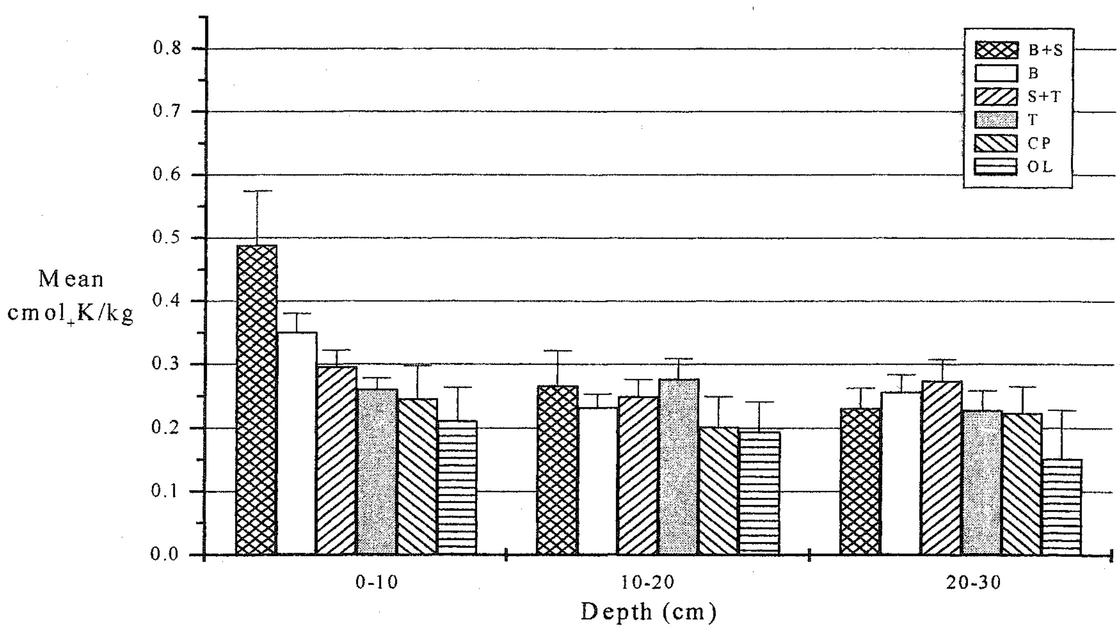


B

Figure 3.9 Mean exchangeable Mn^{2+} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.9A - 1999, Figure 3.9B - 2000.

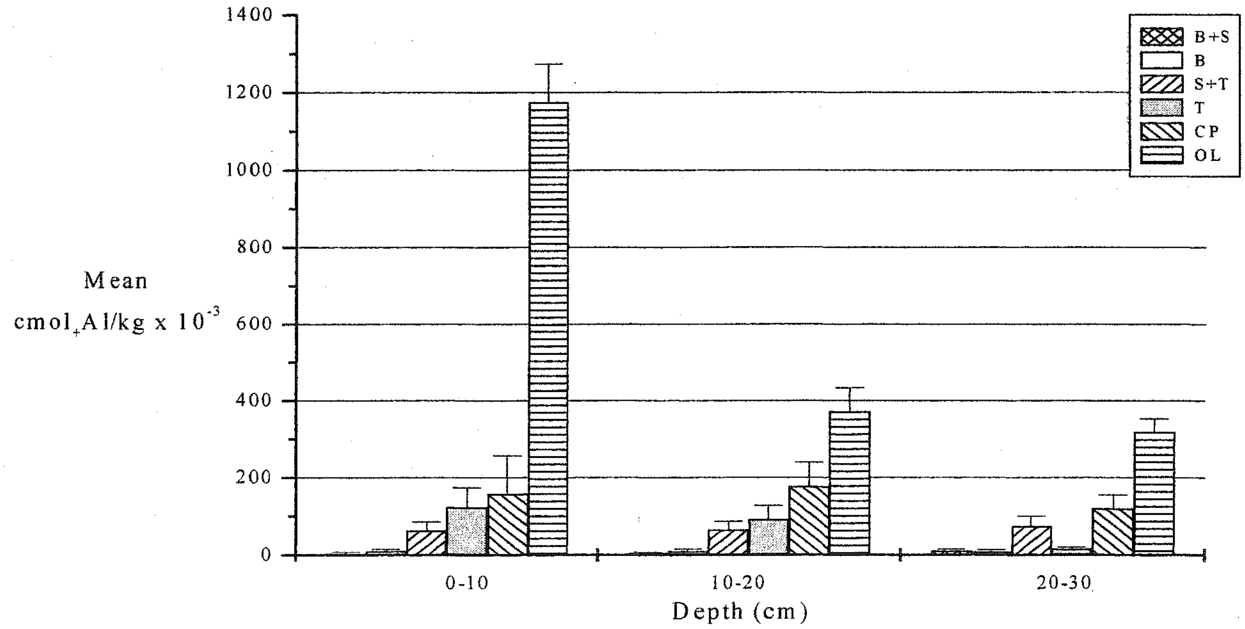


A

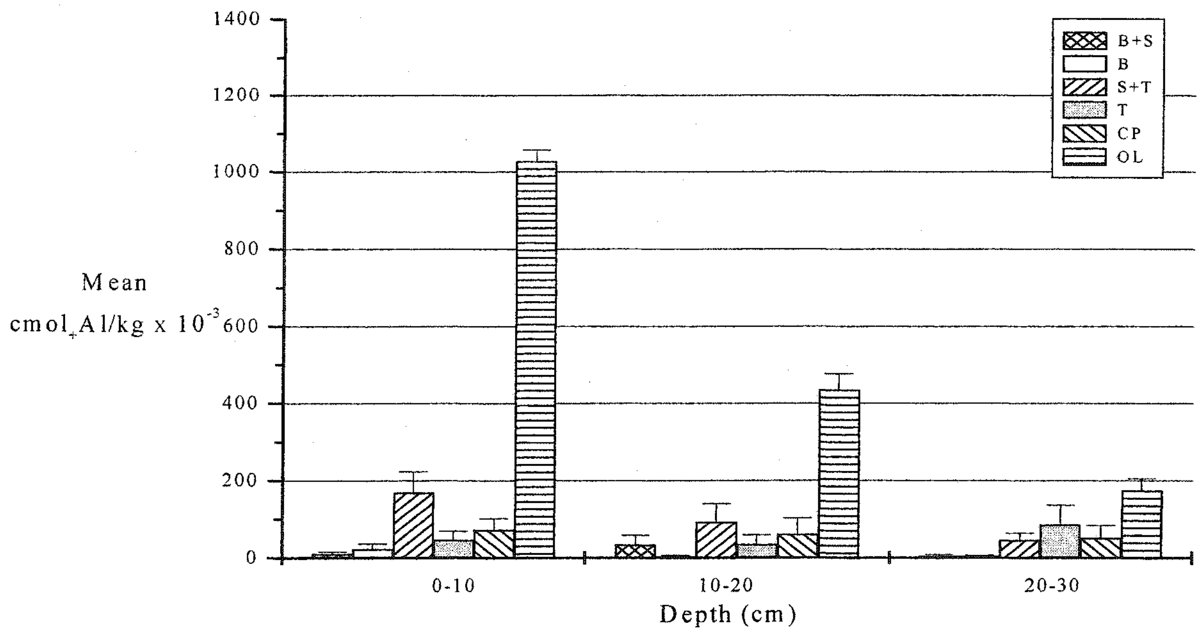


B

Figure 3.10 Mean exchangeable K^+ for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.10A - 1999, Figure 3.10B - 2000.

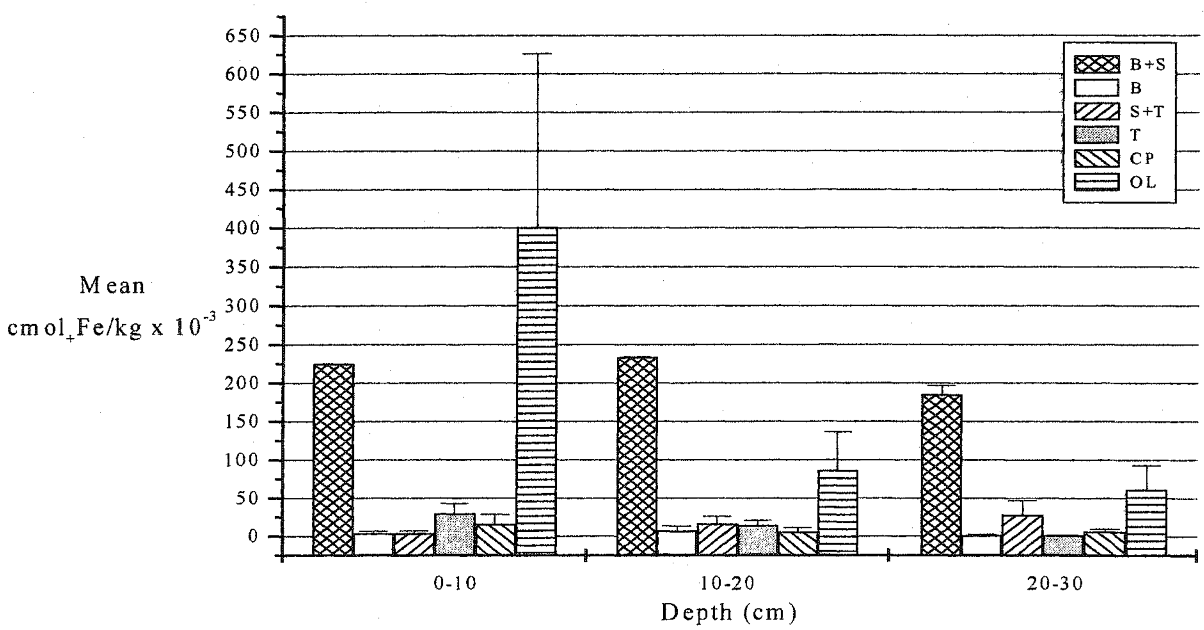


A

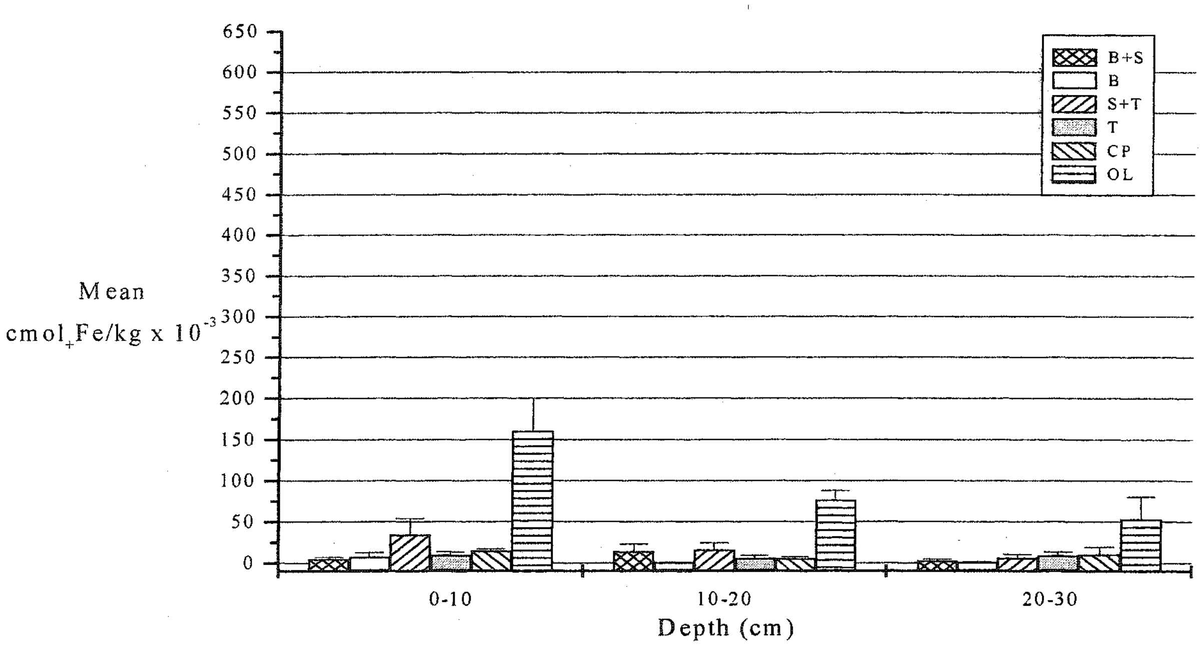


B

Figure 3.11 Mean exchangeable Al^{3+} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.11A - 1999, Figure 3.11B - 2000.

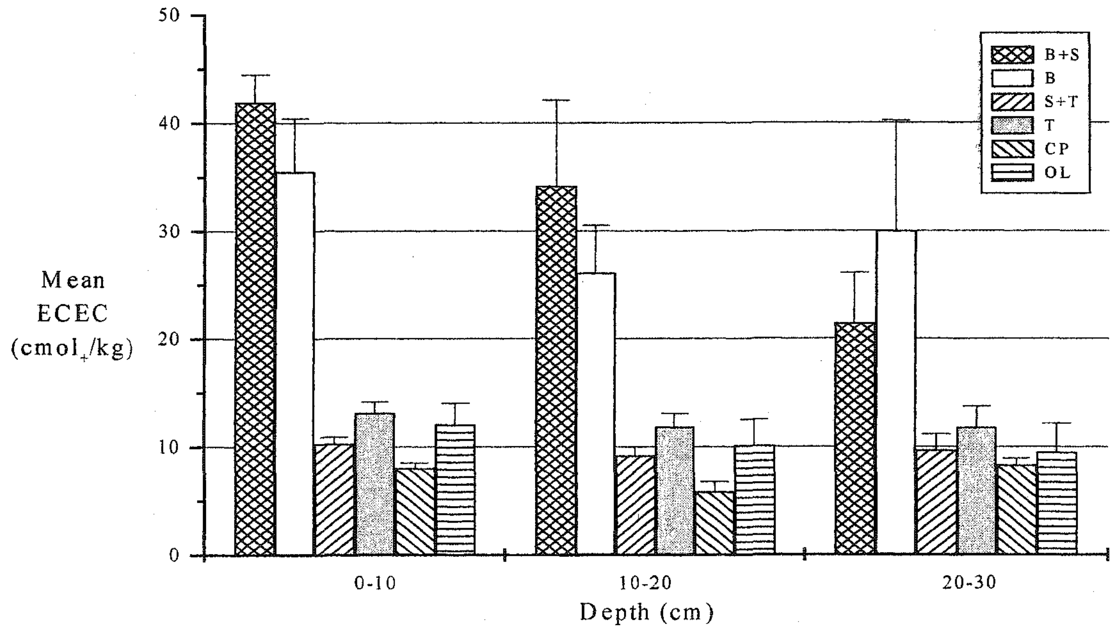


A

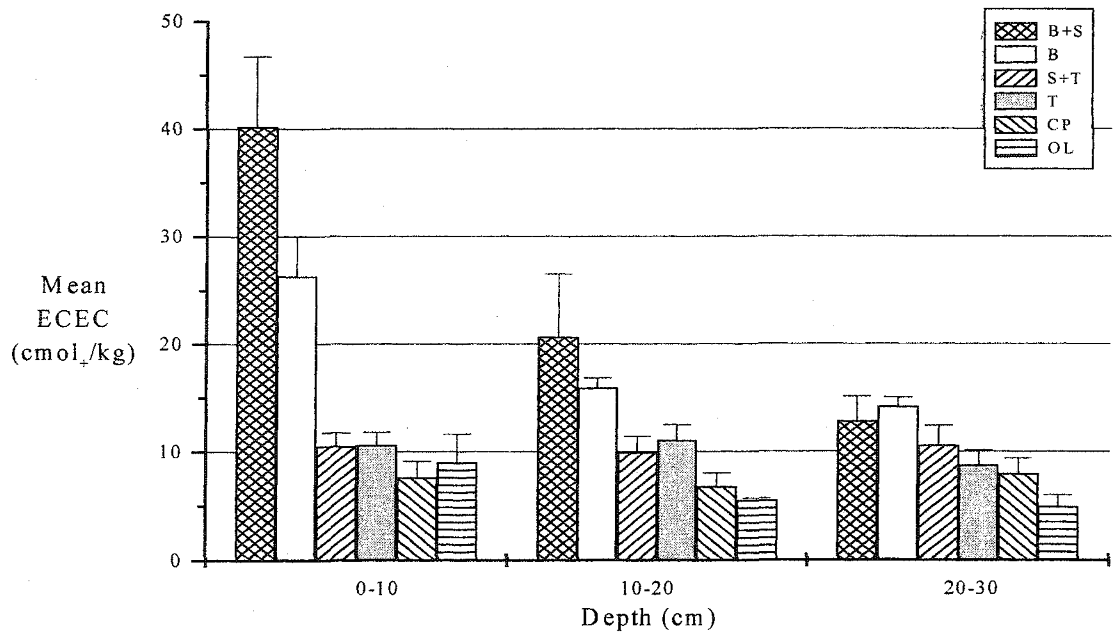


B

Figure 3.12 Mean exchangeable Fe^{2+} for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.12A - 1999, Figure 3.12B - 2000.

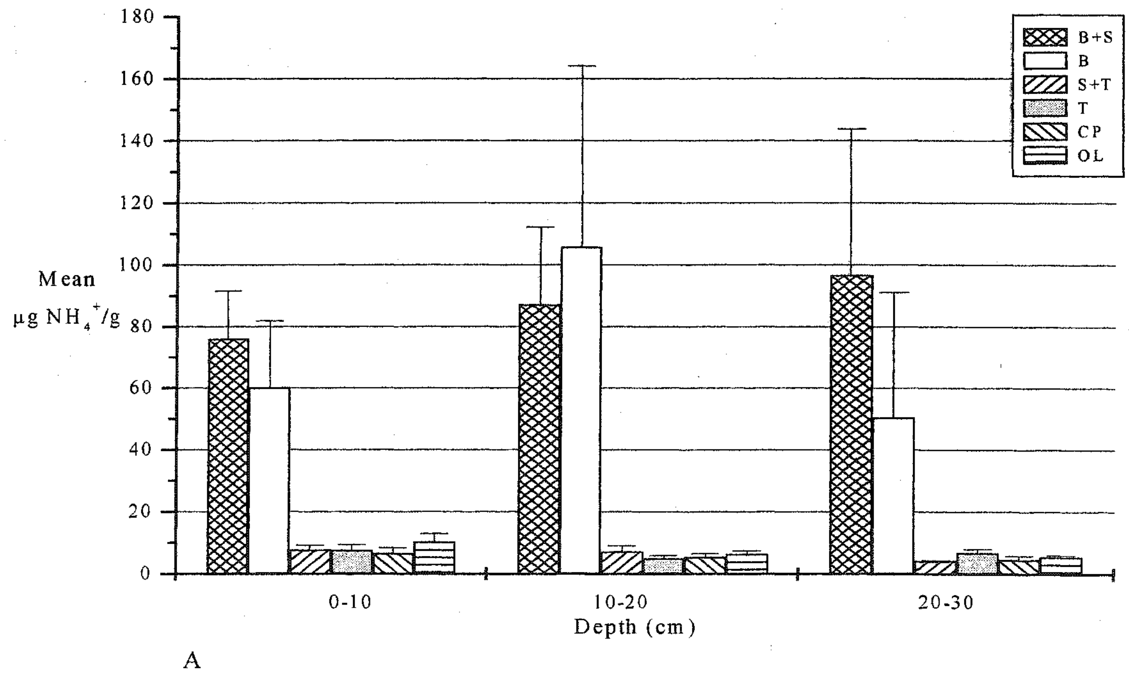


A



B

Figure 3.13 Mean ECEC for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error.
Figure 3.13A – 1999, Figure 3.13B - 2000.



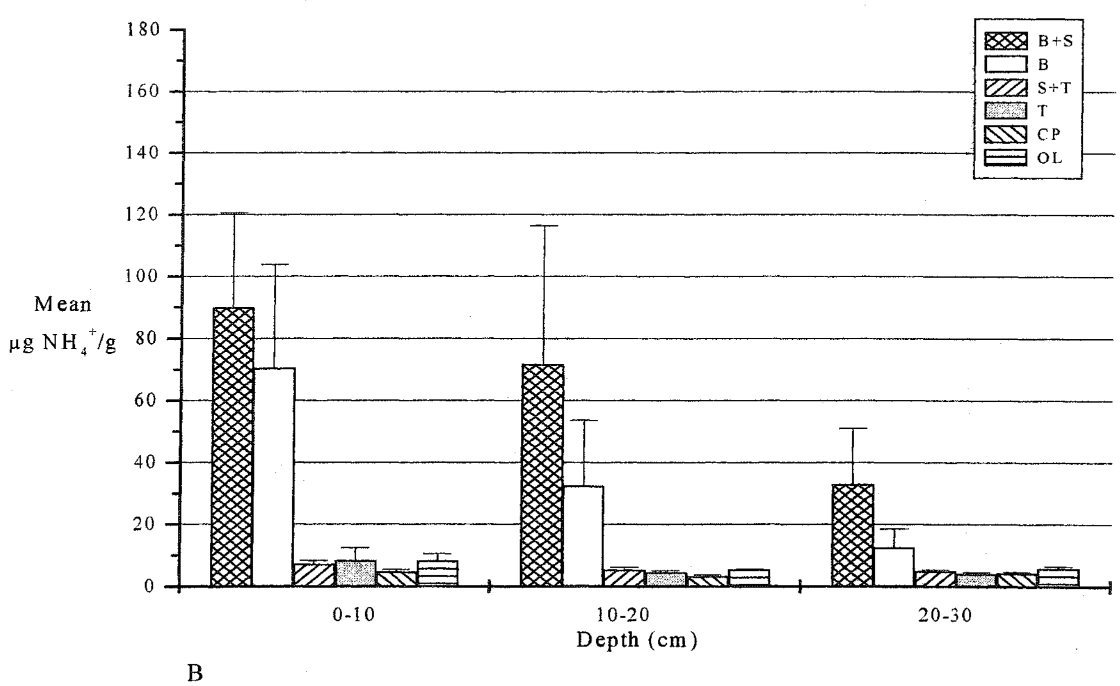
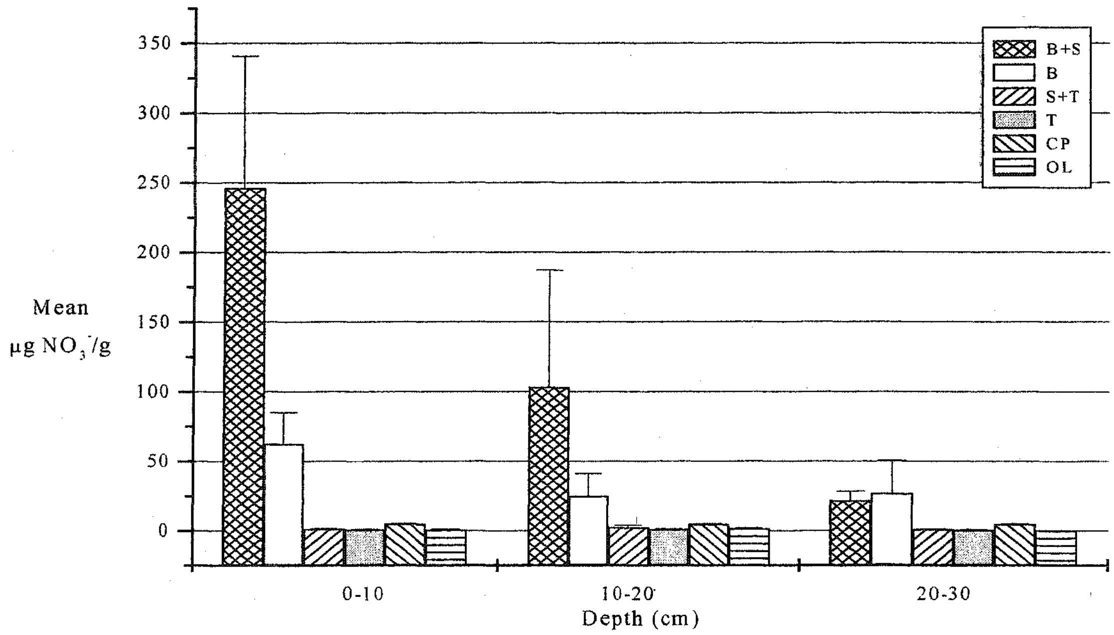
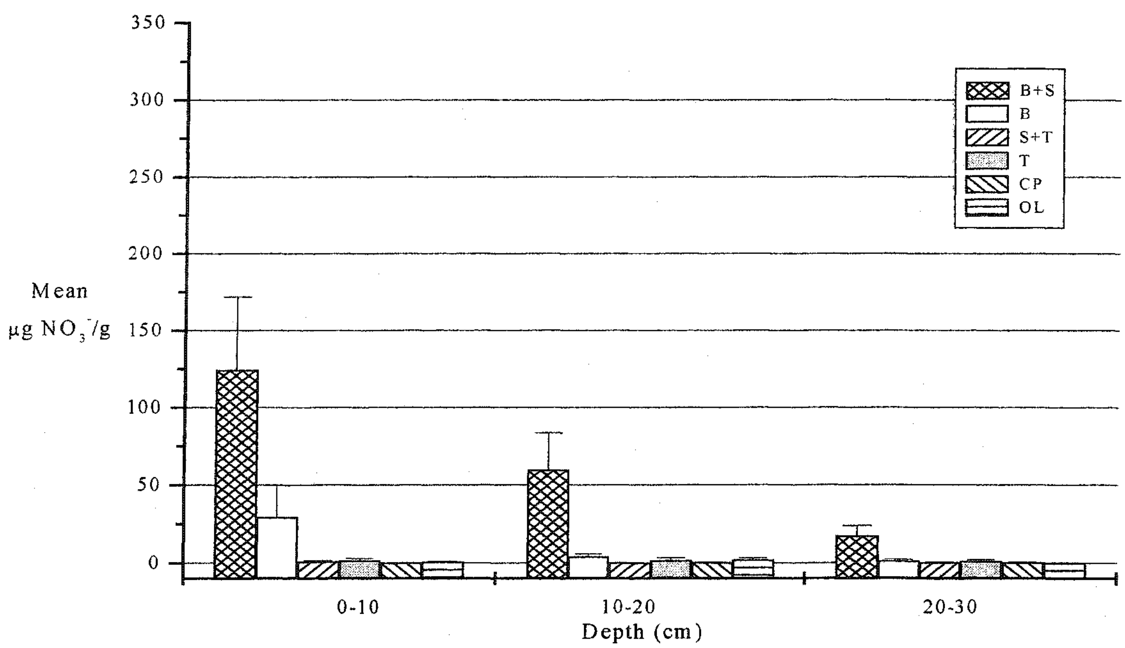


Figure 3.14 Mean available soil NH_4-N for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.14A - 1999, Figure 3.14B - 2000.

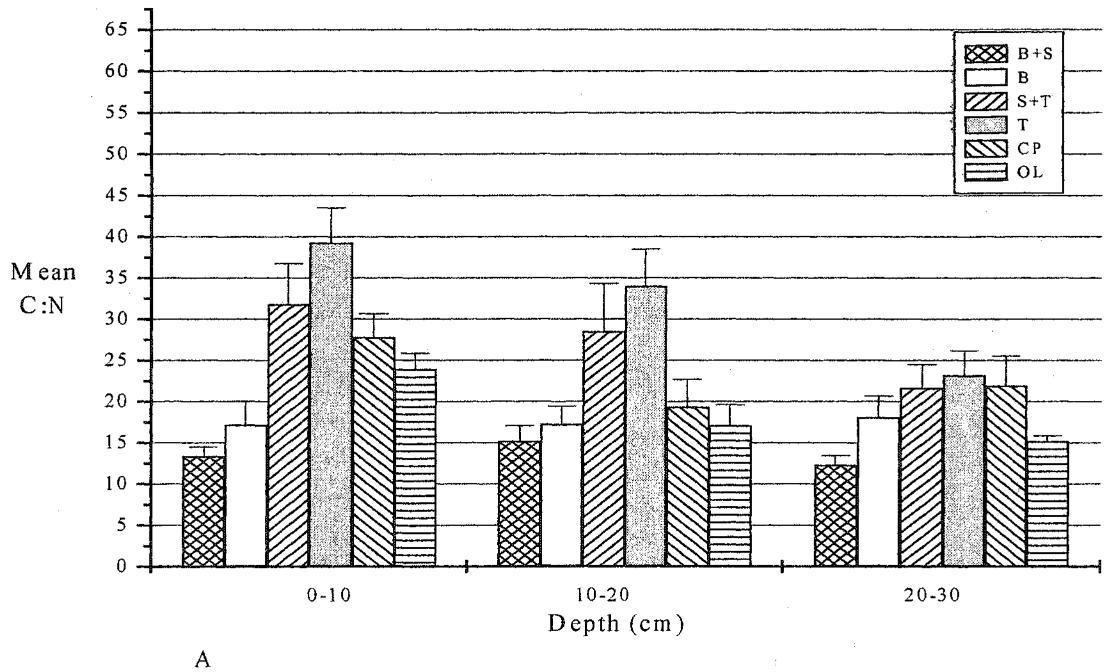


A



B

Figure 3.15 Mean soil NO_3^--N for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.15A gives for results for 1999, Figure 3.15B for 2000.



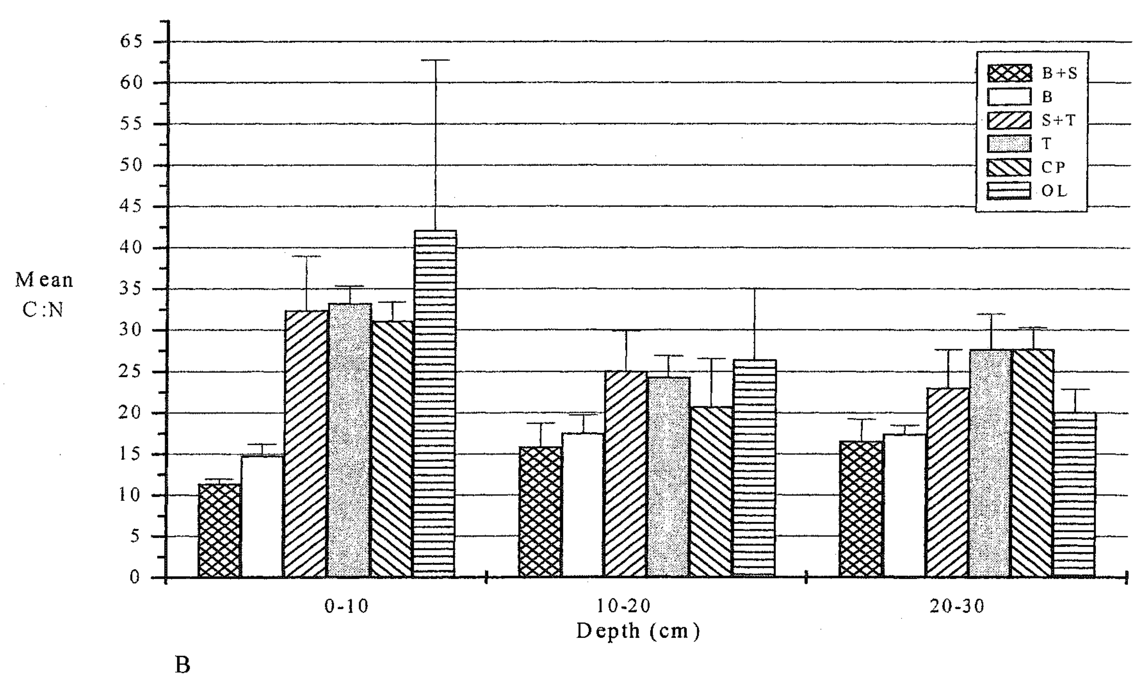
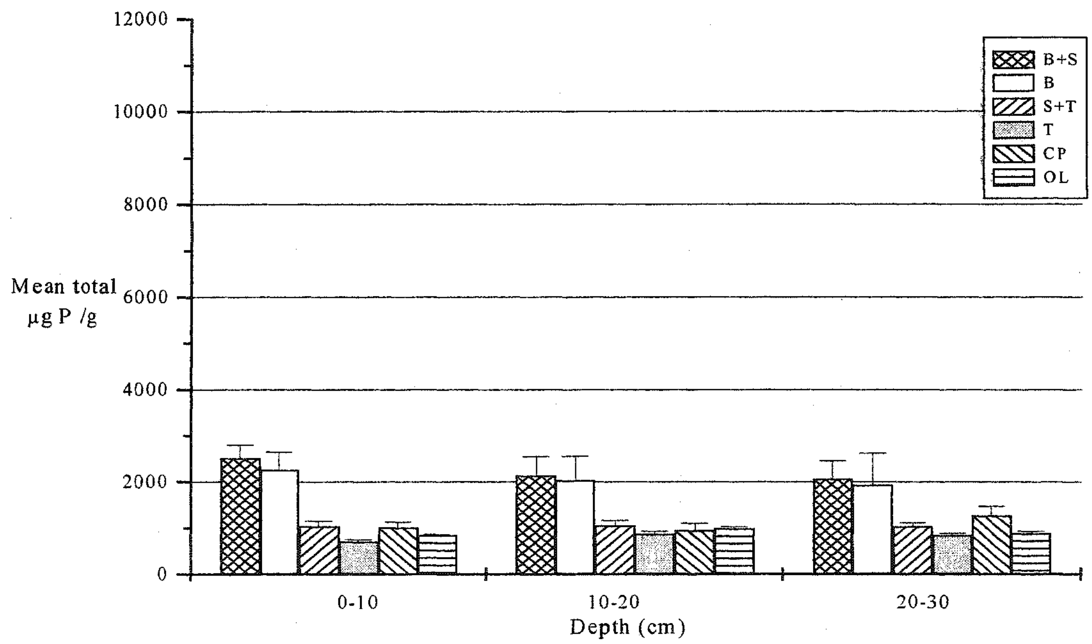
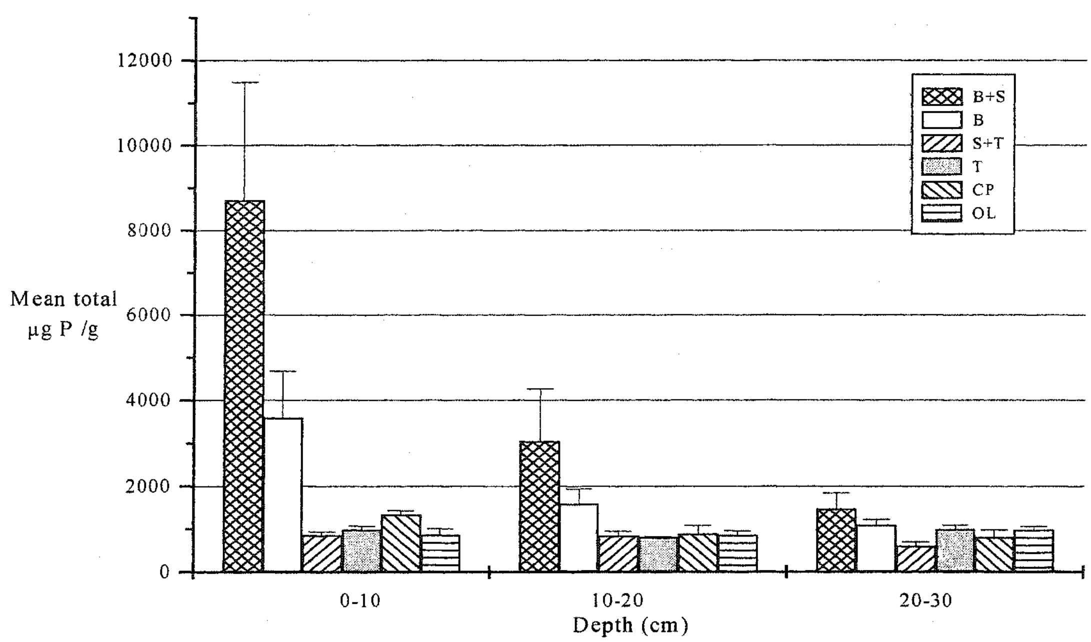


Figure 3.16 Mean soil C:N for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error.
Figure 3.16A - 1999, Figure 3.16B - 2000.

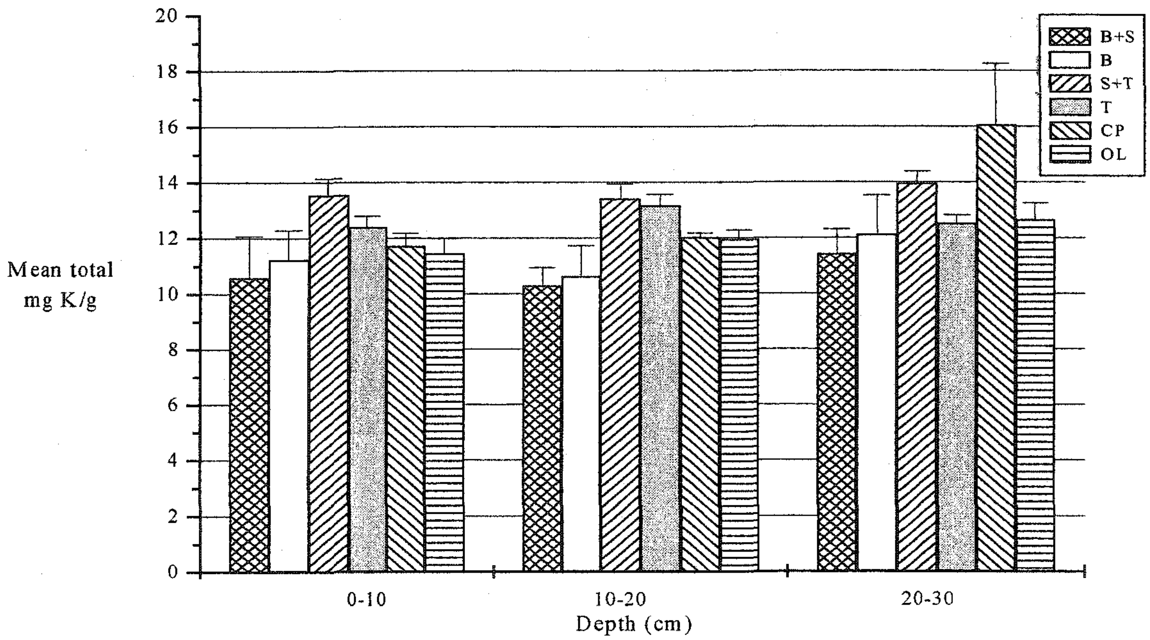


A

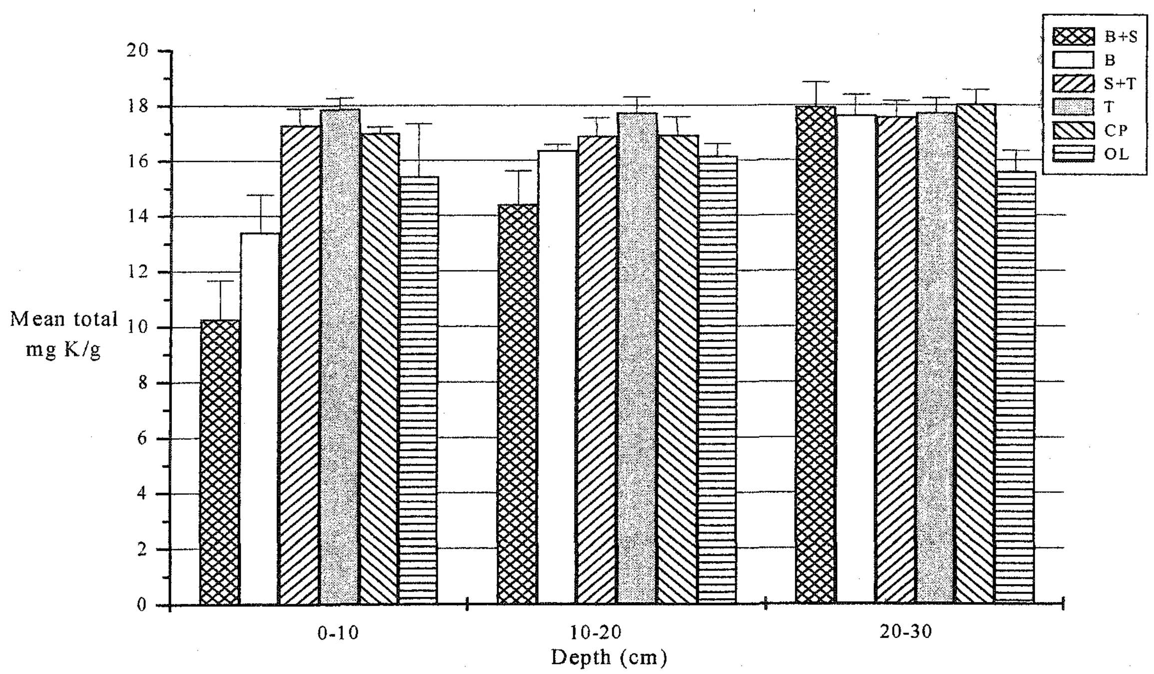


B

Figure 3.17 Mean total soil P for experimental and reference plots of the Clear Lake sites. See 3.3 for sample sizes. Error bars indicate standard error. Figure 3.17A - 1999, Figure 3.17B - 2000.

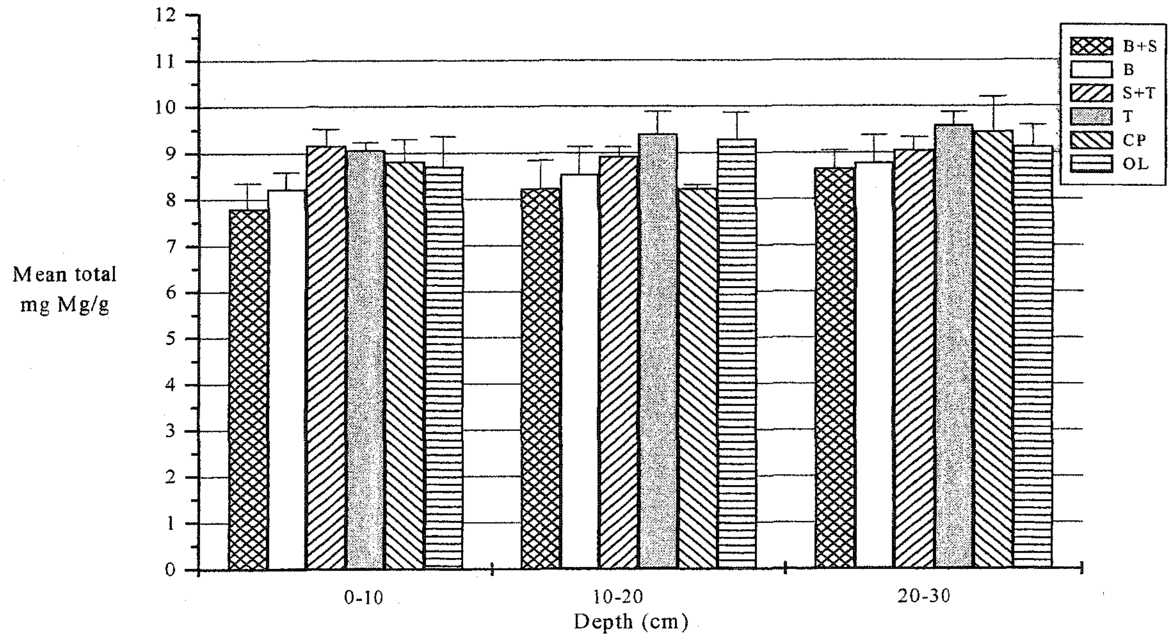


A

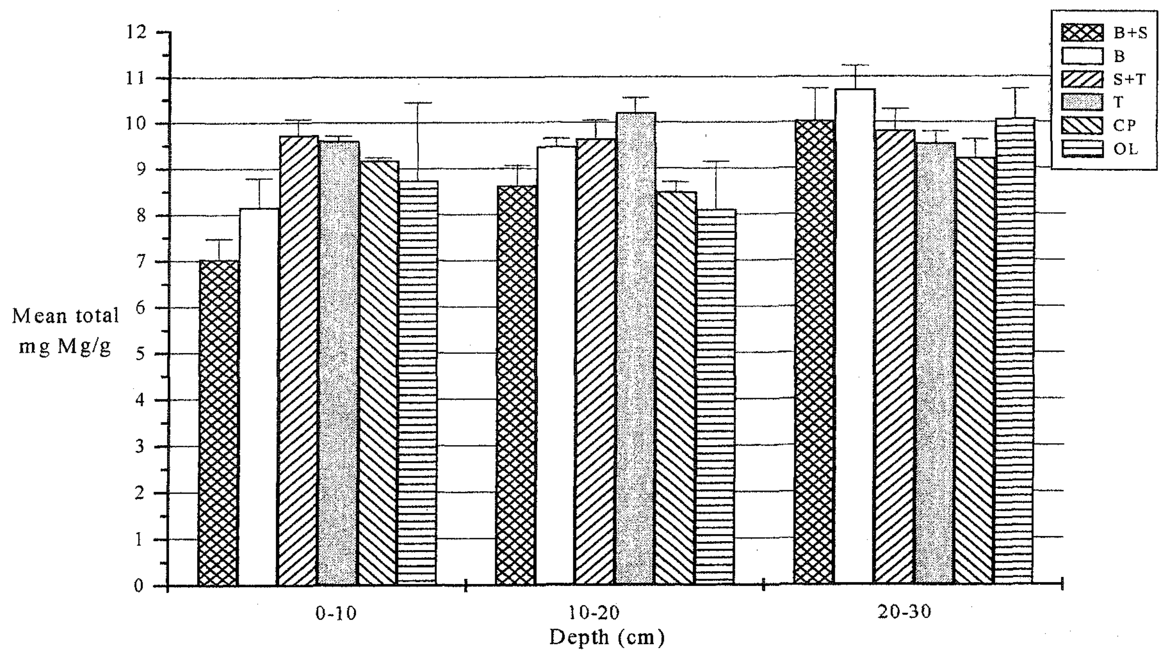


B

Figure 3.18 Mean total soil K for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.18A – 1999, Figure 3.18B - 2000.



A



B

Figure 3.19 Mean total soil Mg for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.19A - 1999, Figure 3.19B - 2000.

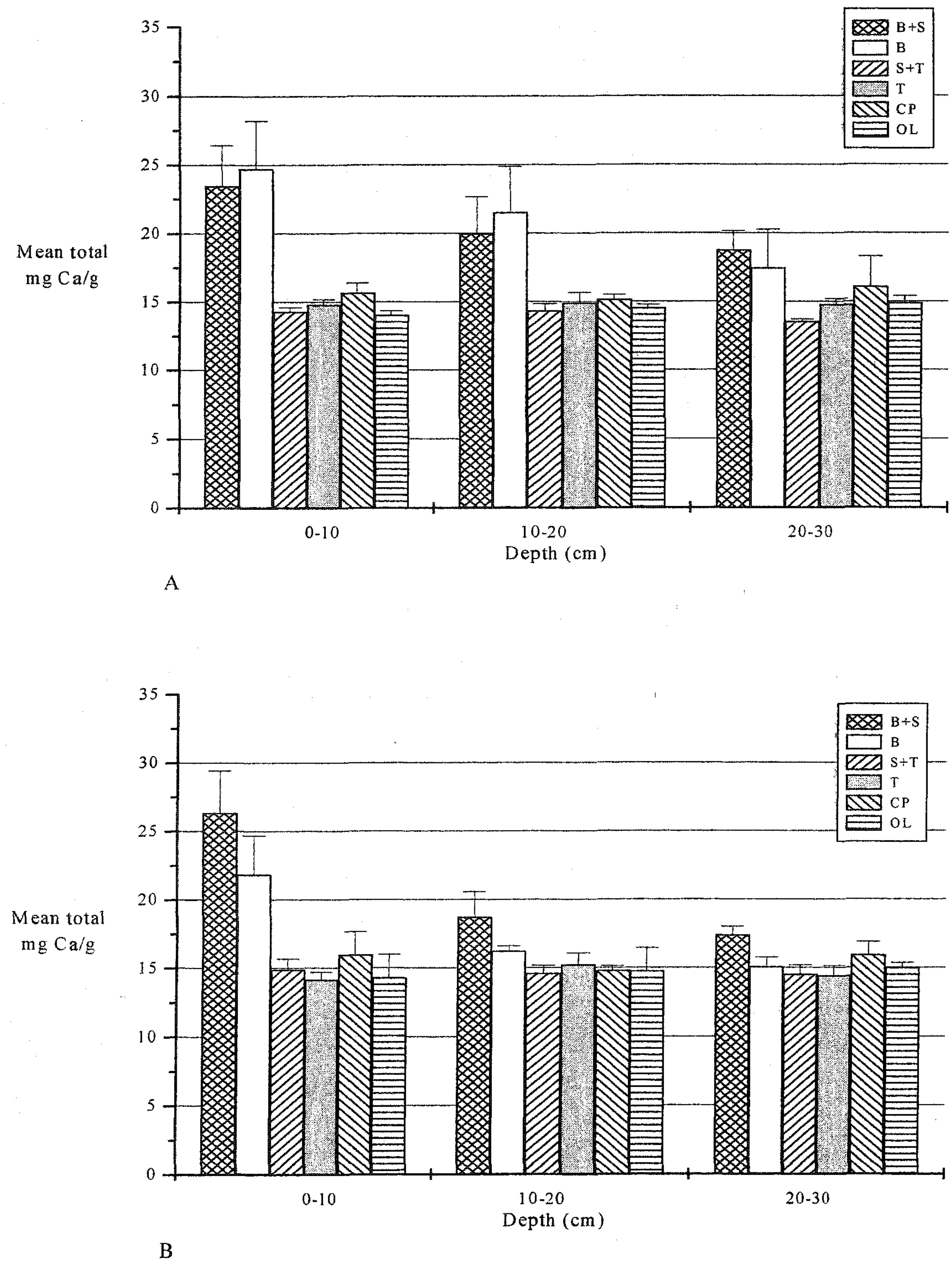


Figure 3.20 Mean total soil Ca for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.20A - 1999, Figure 3.20B - 2000.

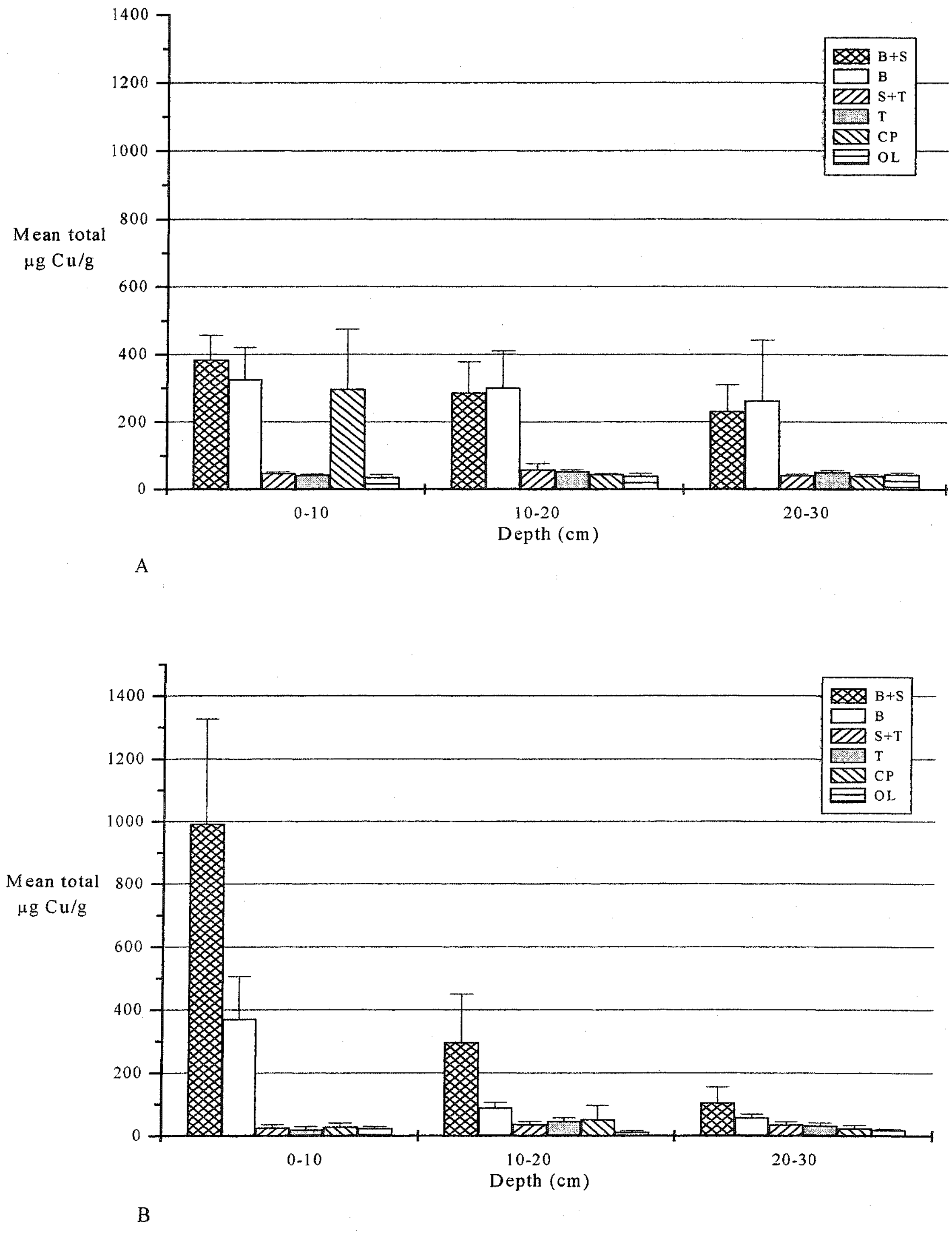
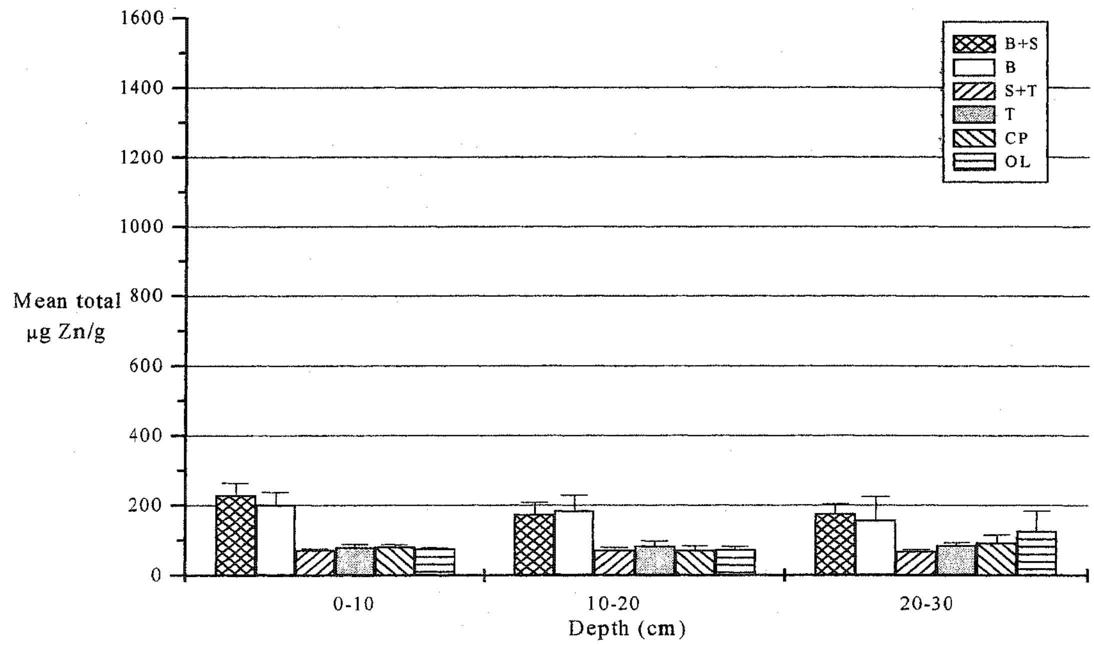
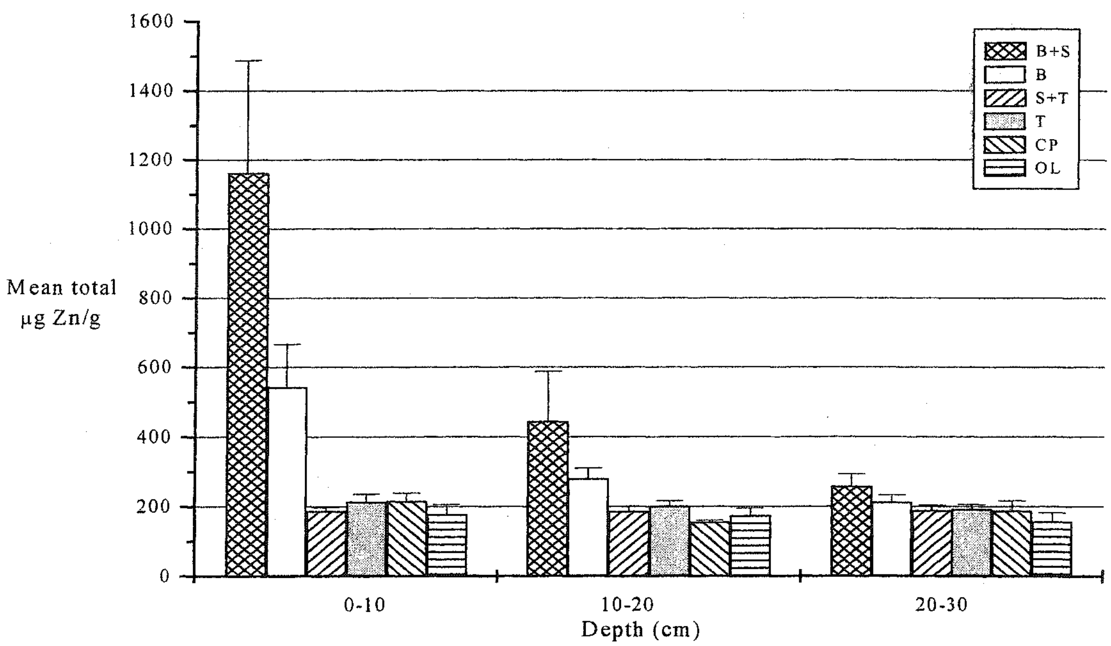


Figure 3.21 Mean total soil Cu for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.21A - 1999, Figure 3.21B - 2000.

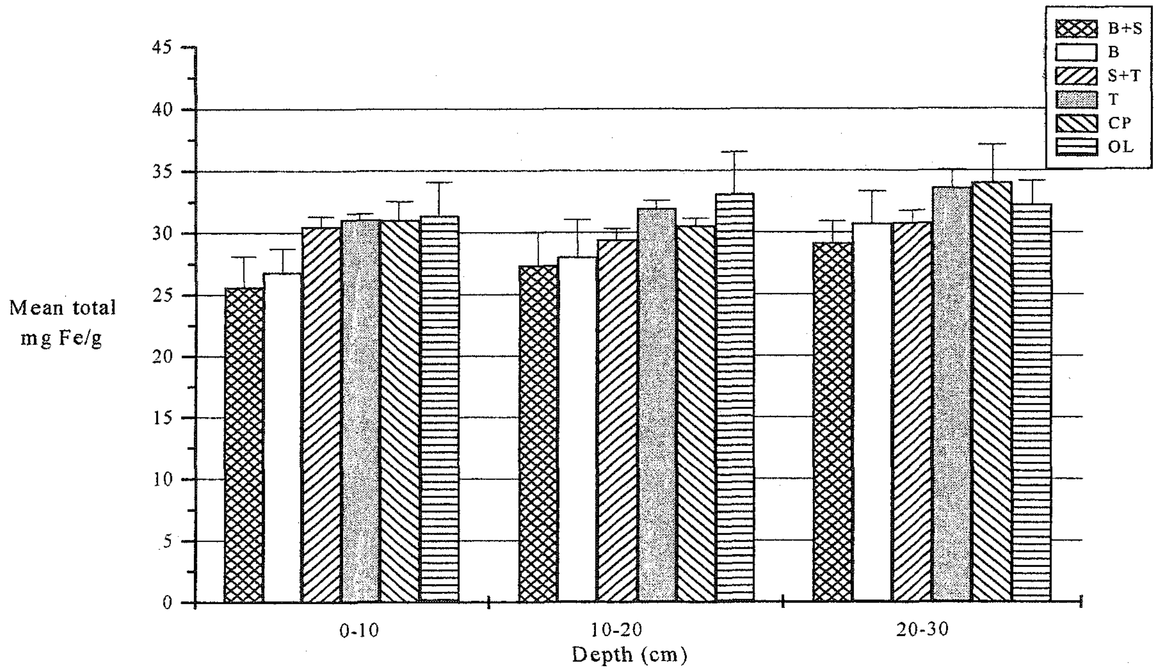


A

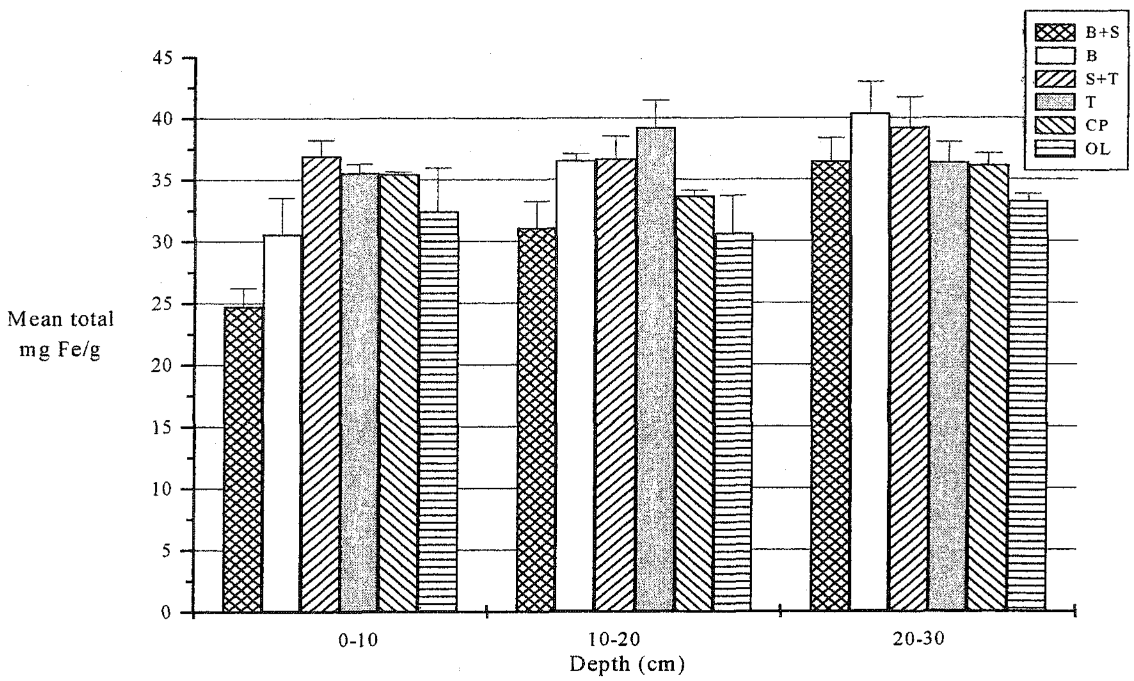


B

Figure 3.22 Mean total soil Zn for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.22A - for 1999, Figure 3.22B - 2000.

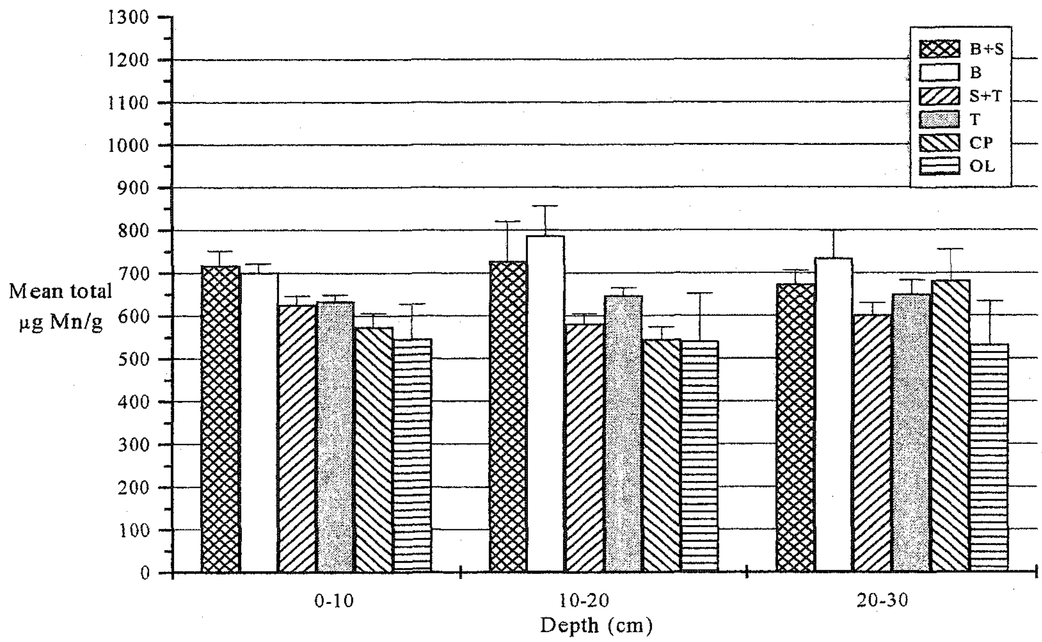


A

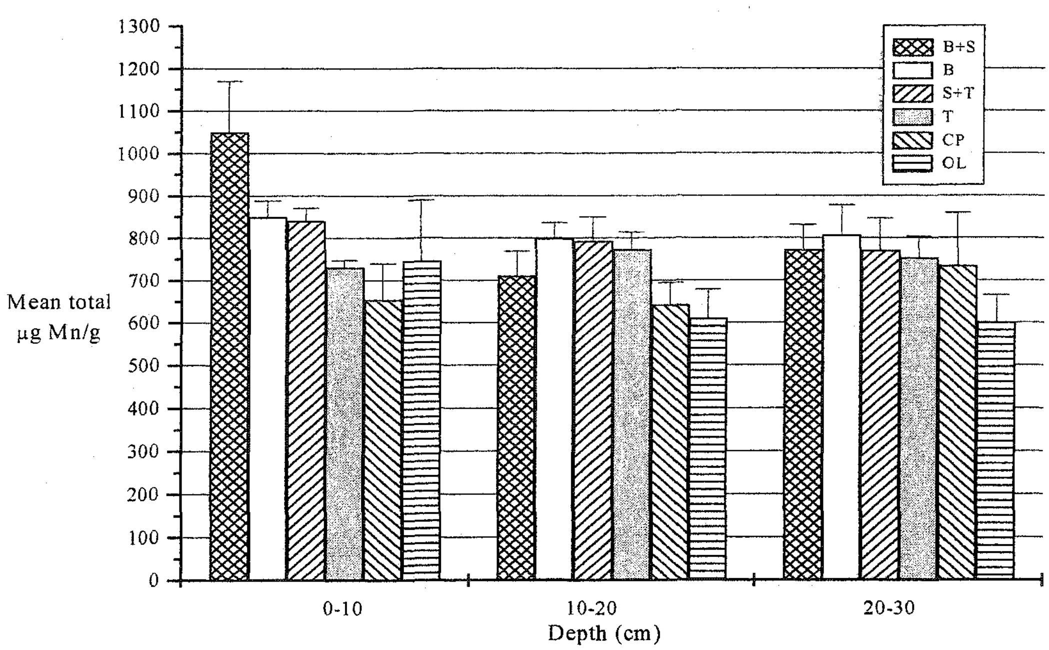


B

Figure 3.23 Mean total soil Fe for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.23A - 1999, Figure 3.23B - 2000.

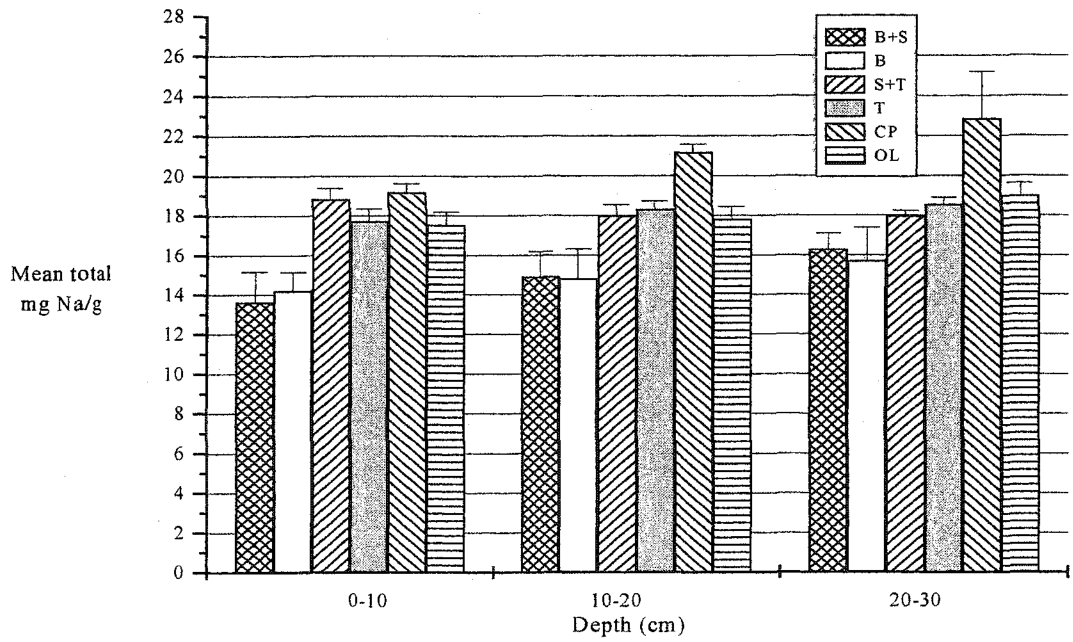


A

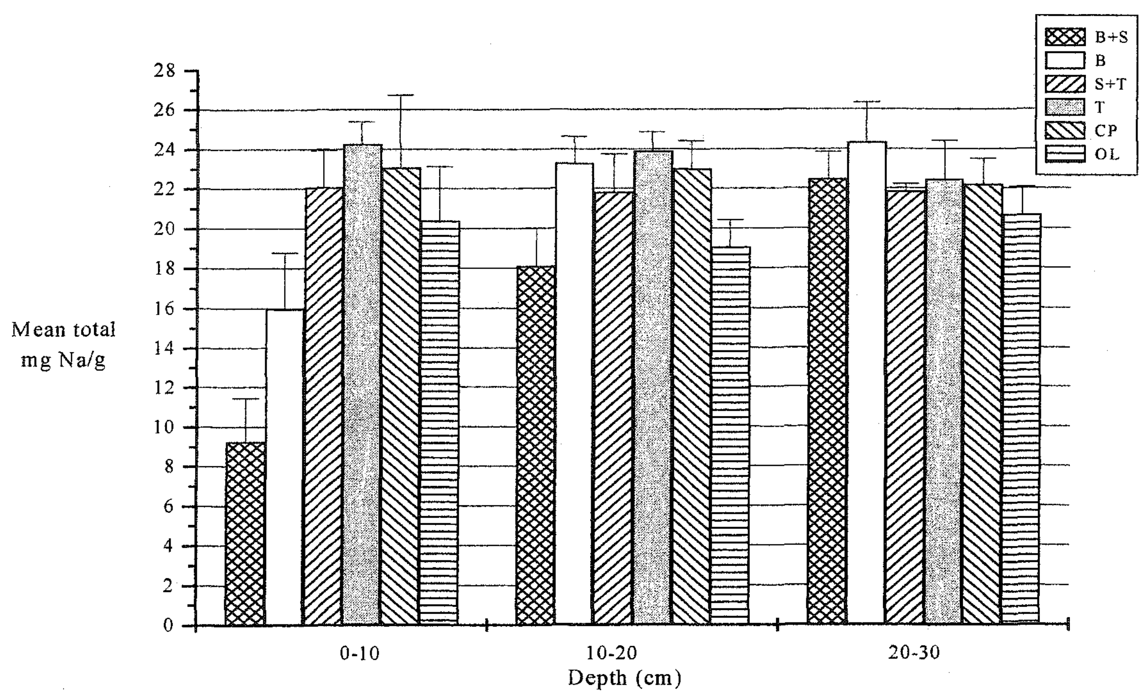


B

Figure 3.24 Mean total soil Mn for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.24A - 1999, Figure 3.24B - 2000.

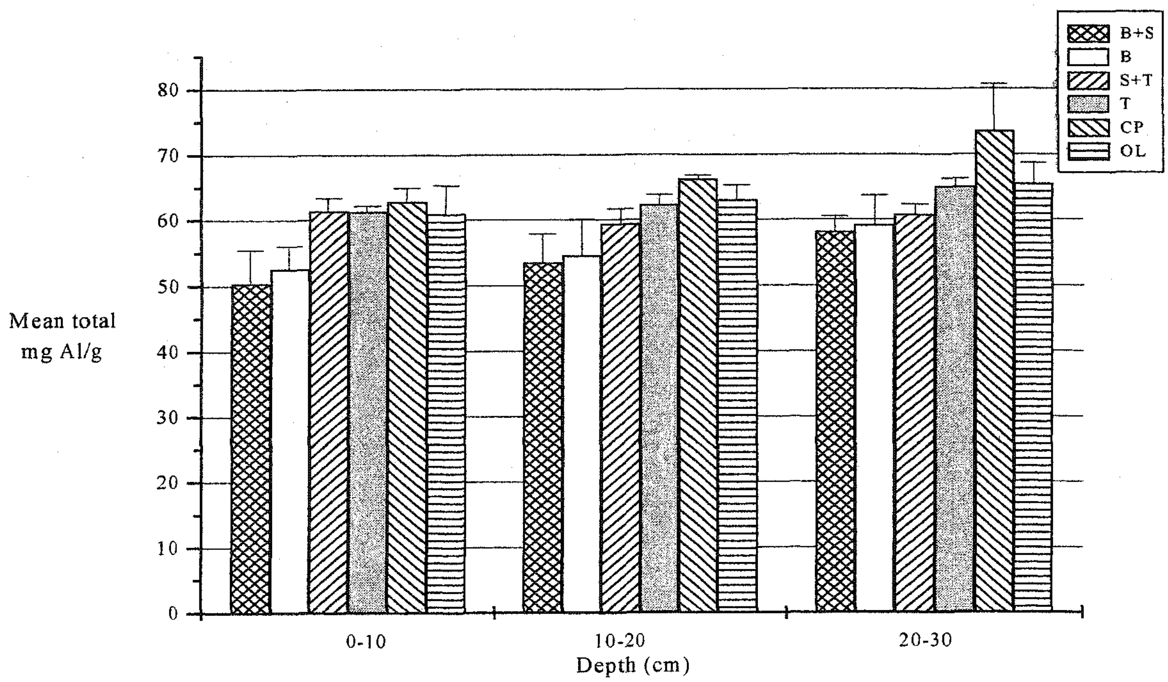


A

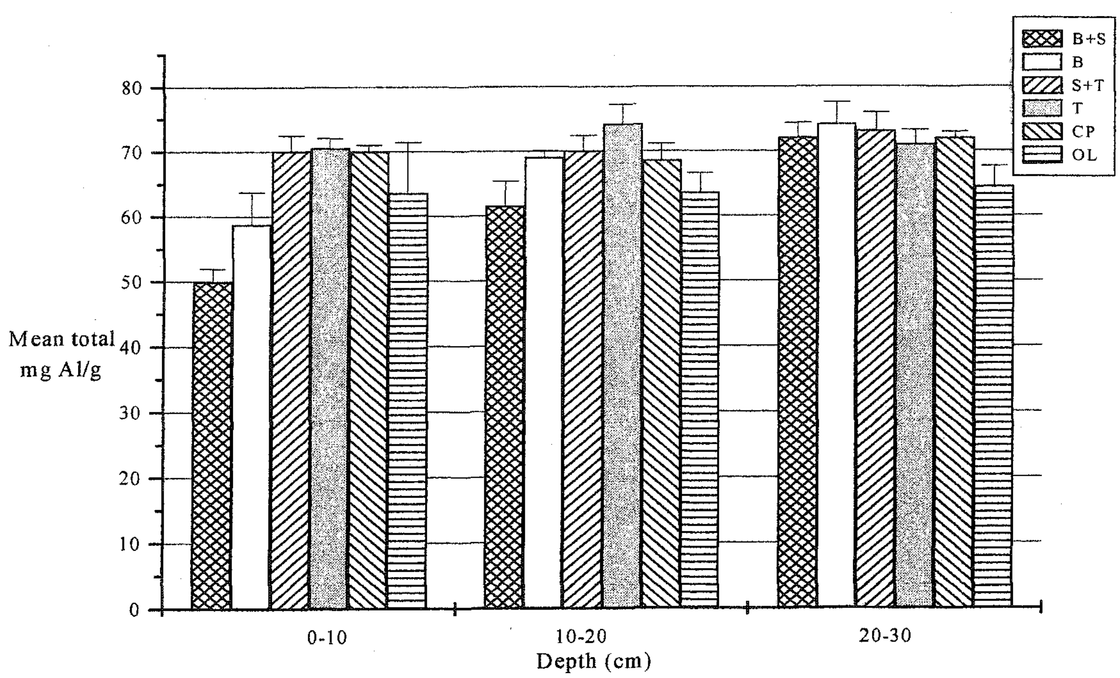


B

Figure 3.25 Mean total soil Na for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.25A - 1999, Figure 3.25B - 2000.

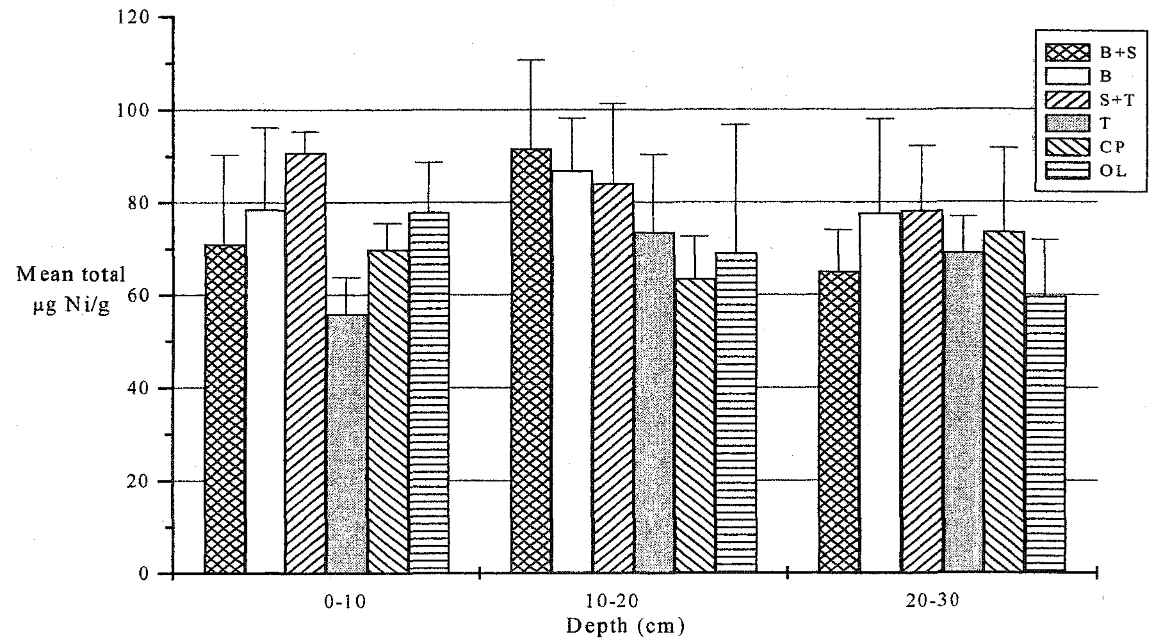


A

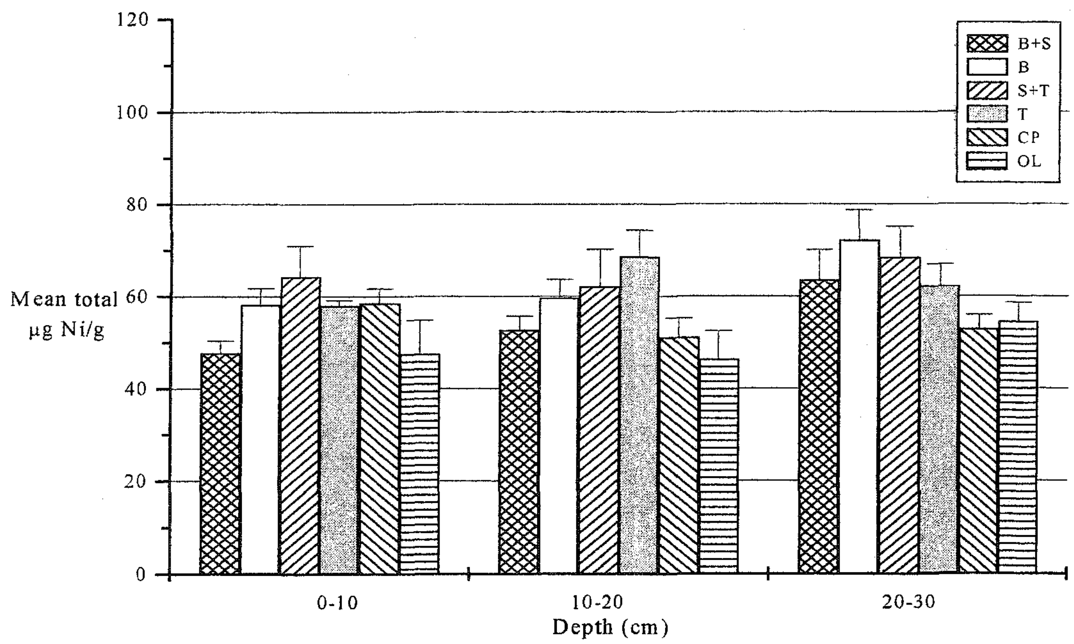


B

Figure 3.26 Mean total soil Al for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.26A - 1999, Figure 3.26B - 2000.

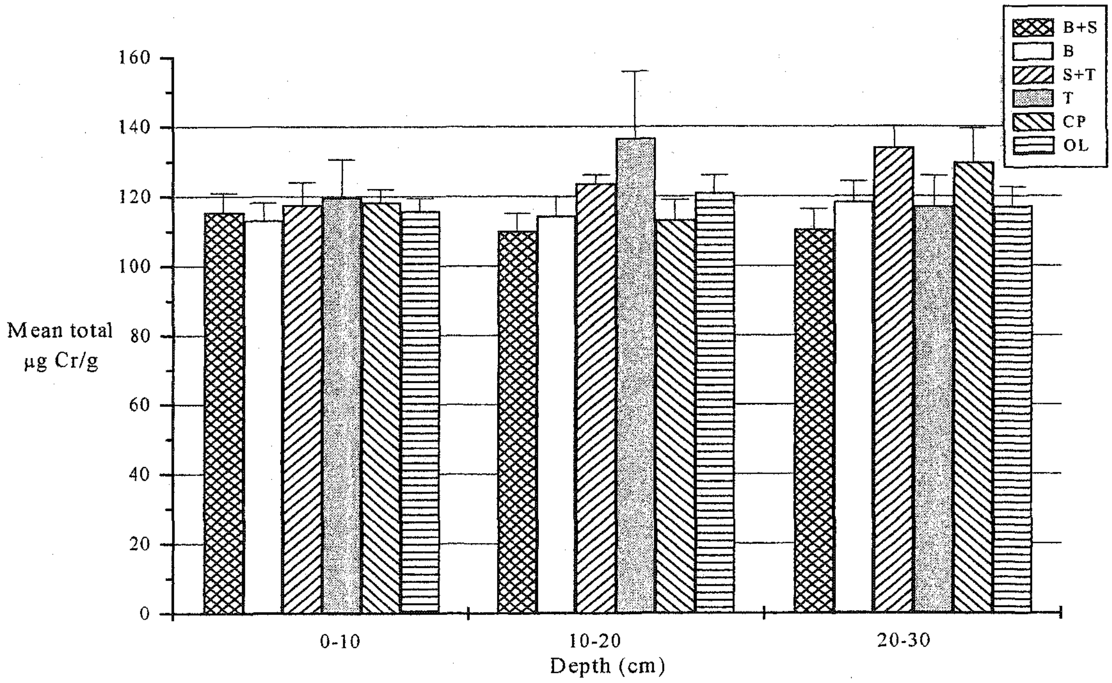


A

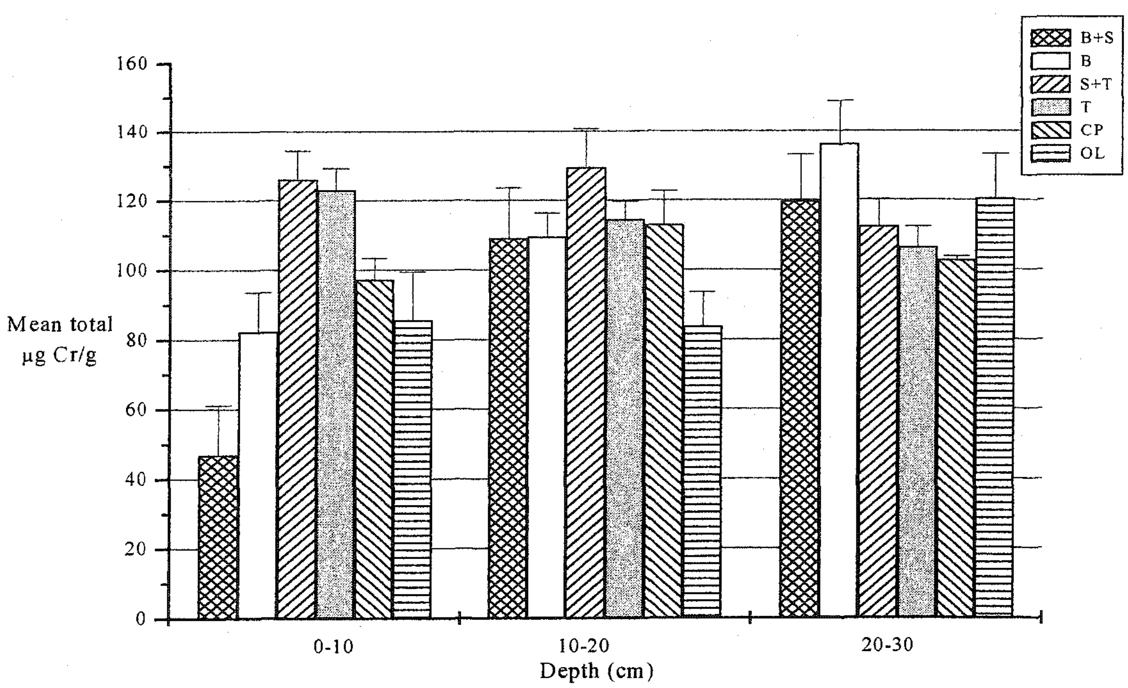


B

Figure 3.27 Mean total soil Ni for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.27A - 1999, Figure 3.27B - 2000.



A



B

Figure 3.28 Mean total soil Cr for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Figure 3.28A - 1999, Figure 3.28B - 2000.

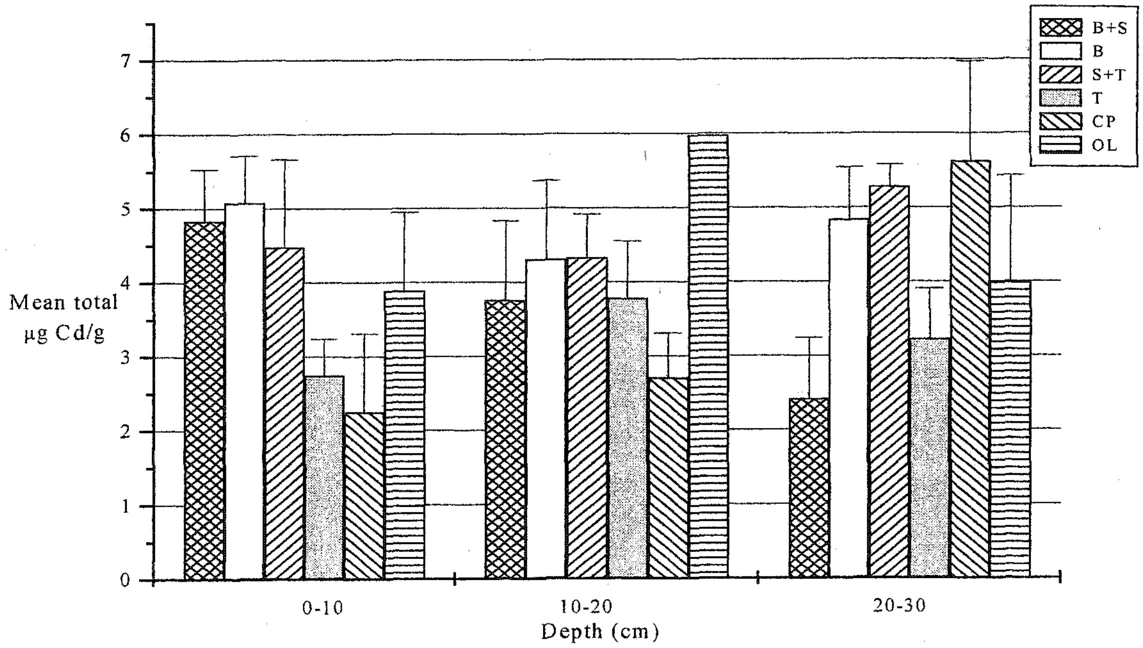


Figure 3.29 Mean total soil Cd for experimental and reference plots of the Clear Lake sites. See Figure 3.3 for sample sizes. Error bars indicate standard error. Results are for 1999. Cd was below detection limits in 2000.

Chapter IV -

Soil solution composition and lodgepole pine *(Pinus contorta* Dougl. *ex* Loud.*)* seedling growth and foliar nutrient status on forest landings reclaimed with tillage, biosolid amendment, and fallow crop seeding

Abstract

Previous studies of landing reclamation have been limited in their success because procedures for applying reclamation techniques had not been fully developed. This type of ecosystem reclamation must be adapted to what equipment and amendments are locally available, hence it is experimental and highly subject to trial and error. This study seeks to add to the body of knowledge available on landing reclamation techniques by providing information on the success of a landing reclamation trial which used tillage, addition of a mixture of land stored primary clarifier waste and municipal biosolids to the soil, and seeding fallow legumes and grasses. The success of the trial was evaluated by measuring soil solution composition (obtained by centrifugation with tetrachloroethylene), foliar nutrient concentrations, and seedling growth (basal diameter, total height, needle length, and leader length). Statistical analysis of results indicated that soil solution pH and concentration of Na and P was unchanged by tillage, in comparison with an untreated control plot. None of the treatments significantly changed soil solution K. Addition of biosolids did not significantly change P concentration in soil solution, but it did result in significantly higher soil solution Ca, and Na in comparison to tillage-treated and control plots. Biosolid amendment did not change soil pH in comparison to tillage treatment, but did significantly elevate pH relative to control plots. Seeding did not produce a significant change in soil solution pH, nor in concentrations of Na, P, K, and Ca.

For the most part, biosolid application did not significantly change seedling height in comparison to control plots or tillage treatment after two growing seasons. Seedlings planted on tillage treated plots were significantly shorter than those on an off-landing control plot. Seedlings planted on an unreclaimed control were also significantly shorter than those on an off-landing control. Several pair-wise comparisons between biosolid-treated, tillage-treated, and control plots were found to be significantly different in needle length. Biosolid-treated seedlings had the shortest needle length (3.7 and 4.7 cm, respectively), S+T and CP an intermediate needle length (5.1 and 5.6 cm, respectively), and OL and T plots had the longest needle lengths (6.6 and 7.1 cm, respectively). Basal diameter of seedlings planted on control plots were not significantly different from seedlings on tillage-treated plots. Basal diameter of seedlings planted on biosolid-treated areas which were seeded with a fallow crop were significantly smaller than that of control plots and tillage-treated plots. None of the treatments produced a significant change in leader height. When biviariate scatterplots of foliar concentration and soil solution concentration of a given element were graphed, few positive or negative trends were shown. Foliar nutrient status of seedlings was not analyzed statistically due to small sample size. However, it is expected that seedlings on plots treated with biosolids and seeded with a cover crop will decline in foliar nutrient status as time continues because of shading by and competition with vigorously growing grasses.

4.1 Introduction

Plants obtain nutrients by absorbing ions dissolved in the soil water (Kozlowski and Pallardy 1997), hence measurements of nutrients in the soil solution may be more helpful in explaining observed plant nutrient deficiencies, or in predicting future site nutrient deficiencies, than total measures of nutrient status in the bulk soil. While there is concern that measurement of ion concentrations in the soil solution is not wholly representative of true conditions in the rhizosphere, information from soil solution is still considered useful in plant nutrition studies and assessment of environmental contaminants (Soon and Warren 1993). Soil solution provides direct measurement of the movement of elements through a soil profile, and several studies have investigated the soil solution composition of lands to which municipal sewage and pulp mill wastes (biosolids) have been added (Koterba et al. 1979, Medalie et al. 1994, Jackson et al. 1999). In the case of forestry landing reclamation, the organic matter and nutrients being supplied by biosolids are necessary for replacing nutrients that have been removed from the landing area and preventing soil recompaction (Kranabetter and Osberg 1995, Sanborn and Bulmer 1996). Such studies showed that the availability of contaminants in sewage sludge and pulp mill wastes depends on the interaction of those contaminants with other elements within the plant or in the soil, soil pH, cumulative and annual metal additions, background levels of contaminants already present in the soil, and soil texture (Pietz 1983, Alberici et al. 1989, Chang et al. 1983).

Once a landing has been reclaimed, more labile nutrients are available and the soil presents a more favorable rooting environment, hence forest productivity should be improved. While evaluation of the soil solution nutrient status alone could be used to assess the success of a reclamation method, it is better to combine soil solution information with foliar nutrient status. Deficiencies in foliar nutrient levels indicate soil nutrient deficiency, inability to access soil nutrients due to extreme soil moisture levels, and/or inadequate root aeration (Kozlowski and Pallardy 1997). Values for landing foliar nutrient levels can be compared not only to off-landing levels, but also to established standards for plant condition (Ballard and Carter 1986). Hence, foliar nutrient levels act as indicators for current conditions and future growth potential.

Many are available which investigate the soil solution composition of areas that have been treated with biosolids (Kraske and Fernandez 1993, Catricala et al. 1996, Koterba et al. 1979, Medalie et al. 1994, Campbell and Beckett 1988). Also available are some studies which pair soil solution analysis with foliar nutrient status analysis, but these generally deal with agronomic species (Bierman et al. 1995, Hue et al. 1988, Jackson et al. 1999, Rengel and Robinson 1990). However, there are almost no studies which combine an analysis of soil solution with analysis of foliar nutrient status of conifers. To date, there are no published studies which investigate forestry landing reclamation, soil solution nutrient status, and foliar nutrient status. Of the studies of landing reclamation which are available, many did not collect data from a reference off-landing plot or untreated control plot, and therefore no inference could be made about how successful treatments were in restoring original site productivity. The objective of this study, therefore, is to use soil solution nutrient composition, foliar nutrient status of planted seedlings, and seedling growth in order to evaluate the success of tillage, biosolid incorporation, and seeding fallow legumes and grasses in landing reclamation. These analyses will also be carried out for an untreated landing plot and off-landing control plot. Comparison of experimental plots with these reference plots will provide a means of assessing how much the treatments improve growth and whether the treatments are capable of producing soil solution and tree growth which are similar to that of an area which has been less disturbed by logging activity.

4.2 Methods

4.2.1 Site description and treatments

In August of 1998, reclamation trials were established on two landings located approximately 30 km south-west of Prince George (Figure 3.1). This region is within the Sub-Boreal Spruce (SBS) biogeoclimactic zone. The soil of the landings was a loam (52% sand, 38% silt, and 10% clay) and the landings were 0.2 and 0.3 ha in size. Soil in the cut block surrounding the landings was a Gleyed Eluviated Dystric Brunisol. Lodgepole pine *(Pinus contorta* Dougl. *ex* Loud.*)* seedlings (1 + 0 container stock) were planted in the study area in the Spring of 1999. Seedlings planted on CP and tillage-treated plots were spaced 1.5 m apart from each other, while those on OL and biosolid-treated were planted 2.0 m apart from each other. A spacing of 2.0 m was not always maintained on biosolid-treated areas as planters avoided putting seedlings in areas where there was puddling. A minimum of 25 trees were planted in each study plot. Soil solution composition, seedling growth measurements, and foliar nutrient status of the seedlings were used as a means of assessing the success of the reclamation trial.

Descriptions of site and reclamation treatments are found in sections 3.2.1 and 3.2.3. In brief, the study used a restricted randomized block design. Each landing was tilled to a minimum depth of 30 cm before organic matter amendments were added. Two sections on each landing were left without organic matter amendment. On the main portion of both landings, muncipal biosolids and land stored primary clarifier waste were mixed with the tilled soil. Half of the biosolid-treated section of each landing was seeded with a mixture of legumes and grasses (biosolid plus treatment seeding treatment or "B+S") and half was left unseeded (biosolid only treatment "B"). One of the two sections left without organic matter amendments was also seeded with the legumes and grasses (seeding plus tillage treatment or "S+T") and one was left unseeded (tillage treatment or "T").

An untreated section of landing; no tillage, no organic matter application, and no seeding was also sampled. This untreated plot is referred to as the control plot or "CP." Also, a plot adjacent to the landings within the cut block was also sampled for the sake of comparison: an off-landing plot or "OL".

4.2.2 Soil solution and soil moisture content

Four sampling locations within each study plot were randomly selected and the same four locations were sampled in 1999 and 2000. Soil samples of approximately 6 kg were taken from 0-10 cm deep in each study plot and placed in individual sealable plastic bags. These samples were refrigerated at 4°C immediately after returning to the laboratory from the field at the end of the day.

Soil solution was extracted by immiscible displacement method using tetrachloroethylene as the displacent. Between 20 and 30 g of field-moist soil was placed in 50 ml Nalgene FEP centrifuge tubes. Tetrachloroethylene was then added to fill the tube to the shoulder and pairs of tubes were balanced to equal weights by drop-wise addition of further tetrachloroethylene. Tubes were then centrifuged at 15,000 rpm (27,000 RCF) for 15 min (Elkhatib et al. 1986). After centrifugation, supernatant was collected using a Pasteur pipette and refrigerated. This process was repeated for a minimum of 8 tubes per sampling site. If the soil from a given sampling site failed to produce 2 ml of soil solution after centrifuging 12 tubes of soil and tetrachloroethylene, it was assumed that the moisture present in the soil could not be removed by this method and the sample was abandoned.

Soil moisture content was assessed by taking a portion of the field-moist sample and weighing it before and after oven-drying for 48 h at 95°C. This temperature was used in keeping with procedures used in section 3.2.5.1. Stones of greater than 3 mm in diameter and leaf litter were removed by hand from the sample before weighing in order to obtain the most accurate measurement possible. Soil percent moisture content (%MC) was calculated as:

$$\%MC = \frac{\text{wet weight} - \text{dry weight at } 95°C}{\text{dry weight } 95°C} * 100$$

4.2.3 Plant growth measurements

Ballard and Carter (1986) recommend measuring a minimum of 15 trees per study plot. This was very difficult in biosolid-treated plots. The high density of seeded legumes (B+S) and of naturally regenerating plant species (B). As a result, finding the lodgepole pine seedlings was challenging and the seedlings were in danger of dying from competition and from snow-press. In the event that a tree died or was lost, a new tree was selected for measurement. As a result, sample sizes for each sampling interval were not equal. In order to find the seedlings more easily, the fallow legumes and grasses were pressed and stomped down around the seedlings to a diameter of 1 m in the summer of 1999 and 2000. Due to a concern that snow-press from the grasses would harm the seedlings, the grasses were mowed with a brush saw in the Fall of 1999 to a diameter of 1m from the seedlings.

Diameter growth was determined by calipers placed as close to the base of the seedling as the soil microtopography would allow. Total height was measured from as close to the root collar as possible to the top of the apical meristem. Leader growth was taken from the node closest to the apical meristem to the tip of the apical meristem. Leader growth was not measured until Fall 2000 because leader dominance was not evident until that time; no node from which to measure the leader was evident. Average needle length for each tree was approximated visually by laying a ruler along a minimum of 5 fasicles of the current year's growth.

At the end of the study, three trees were harvested from each study plot for obtaining root to shoot ratio values and evaluating root morphology. However, assessment of root morphology and root mass was abandoned for a number of reasons: soil could not be removed from the root plugs to produce reliable measures of root surface area and root mass, a proper root washing facility was not available, and lack of labour resources to spend on this time-consuming procedure.

4.2.4 Foliar nutrient analysis

Current year's growth composite foliar samples of approximately 2 g (oven-dry weight) were collected in the Fall of 1999 and 2000 from between 10 and 15 trees per plot. Ballard and Carter (1986) recommend sampling a minimum of 15 trees per plot, however this was not possible on all plots as a conscious effort was made to sample as little as possible from trees being measured for growth parameters. Some foliar samples were also collected following planting of the seedlings in the Spring of 1999 to indicate initial foliar nutrient status. Before analysis, samples were oven-dried at 70 °C and ground using a coffee grinder.

Digestion of foliar samples, each weighing approximately 0.2 g, was accomplished by microwave acid digestion with 6ml of HNO_3 and 1.5 ml of H_2O_2 (each 37% concentration). This procedure gives a homogeneous solution (Dick, pers. comm. 2002) and is the standard method for organic matter digestions used at Central Equipment Laboratory of the University of Northern British Columbia. The microwave program used for this digestion is the same as that used for total nutrient analysis of soil (see section 3.2.5.6) but the program was run only once. Following digestion, the samples were transferred to a 50 ml volumetric flask and nanopure H_2O was added till the total volume was 50ml. The samples were then stored in Nalgene containers and sent for ICP-AES analysis of Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, and Zn.

Ground subsamples were also analyzed for total C (%C) and total N (%N) by a Fisons Instruments elemental analyzer (NA 1500 NC). A thermoconductivity detector (TCD) in the elemental analyzer evaluates the amount of C and N present when samples are ignited at 900 to 1050°C. Peaks generated by the TCD are converted to %C and %N by sample mass (Essler, pers. comm. 2002).

4.2.5 Statistical analysis

This study had a restricted complete randomized block design with unequal sample sizes. Statistical analysis of seedling growth data was conducted on only results from Fall of 2000. Statistical comparison of seedling growth data between seasonal measurements would have violated the assumption that there is no pattern in missing data (Tabachnick and Fidell 2001): seedling mortality (Table 4.1) was highest on B+S plots, hence the majority of missing data would have come from B+S. Soil solution nutrient levels were also treated to statistical analysis. Sample size for foliar nutrient levels was small (less than three), hence only descriptive statistics are given for foliar nutrient analysis.

Measurements of seedling height, leader length, needle length and basal diameter taken in Fall of 2000 had no univariate or multivariate outliers. All four variables used for analysis of differences in seedling growth were sufficiently close to being normally distributed, hence no transformations were performed. Basal diameter and needle length had significant Leveene's tests ($p = 0.002$ and 0.046, respectively), hence Tamhane's T2 was used as the test statistic for these variable in post-hoc comparisons. Bonferroni was the test statistic used for seedling height and leader height. In the multivariate tests, Pillai's Trace was used as the approximation for statistical significance because it is the most robust when sample sizes are unequal (Tabachnick and Fidell 2001). As in Chapter III, a traditional α of 0.05 was used for multivariate tests of variance.

As in Chapter III, a Bonferroni-type correction was made for between-subject effects, the Dunnett was used for planned comparisons of experimental and control means with an α of 0.05, and post-hoc comparisons were done with a Bonferroni correction to α for protecting against inflated Type I error. The Bonferroni-type correction (see section 3.2.3) for between-subjects comparisons in seedling growth data was:

$$\alpha = 1 - (1- \alpha_1)(1- \alpha_2)(1- \alpha_3)(1- \alpha_4)$$
$$\alpha = 1 - [(1-0.013)]^5$$
$$\alpha = 0.0510$$

As with Chapter III, the Dunnett method was used to make the following comparisons:

H_1: S+T = CP
H_2: T = CP
H_3: B+S = CP
H_4: B = CP
H_5: S+T = OL
H_6: T = OL
H_7: B+S = OL
H_8: B = OL
H_9: CP = OL

Comparisons between experimental treatments were done post hoc using the Bonferroni correction of α and the Tamhane's T2 test statistic. The post-hoc comparisons were as follows:

H_{10}: S+T = T
H_{11}: B+S = B
H_{12}: B+S = S+T
H_{13}: B = T
H_{14}: B+S = T
H_{15}: B = S+T

Distributions of some of the elements in soil solution were skewed and required transformation in order to satisfy MANOVA assumptions of normality (Tabachnick and Fidell 2001, Sokal and Rholf 1995). A logarithm transformation was used for soil solution Ca, an inverse for Na, and the square root of K. None of the variables were checked for outliers since there was not a sufficient sample size to delete atypical observations. As with Chapter III soil analysis, the list of dependent variables available for statistical analysis in soil solution outstrips the guideline of having a sample size equal to or greater than the number of dependent variables (Tabachnick and Fidell 2001). In order to maintain a format similar with that of Chapter III, the variables selected for analysis are the same as those used in Chapter III: pH, Na, P, K, and Ca (with transformations as stated above). Those variables which were selected for analysis in Chapter III were included because of the importance in soil-plant ecology. Except for inverse soil solution Na, all variables violated the assumption of homogeneity of variance, hence Tahmane's T2 was used in planned comparisons as it compensates for unequal variances. In the case of inverse soil solution Na, the Bonferroni approximation was used since heterogeneity of variance was not present. In the multivariate tests, Pillai's Trace was used as the approximation for statistical significance and traditional α of 0.05 was used for multivariate tests of variance. Between subjects were evaluated with the following corrected α:

$$\alpha = 1 - (1-\alpha_1)(1-\alpha_2)(1-\alpha_3)(1-\alpha_4)(1-\alpha_5)$$
$$\alpha = 1 - [(1-0.01023)]^5$$
$$\alpha = 0.0501$$

Planned and post-hoc comparisons were done as described above for seedling growth measurements.

As per Chapter III, values for eta squared (η^2) have been provided in the statistical tables of this report in order to provide the context for interpreting the degree to which a main effect or interaction influences the variance of a measure (Tabachnick and Fidell 2001, Kirk 1996).

The model used for MANOVA on seedling growth measurements had only one independent variable: Treatment. The model for analysis of soil solution composition included Year, Landing, and Treatment. For the reasons mentioned in section 3.3.1, Landing will not appear in the tables of statistical results presented herein.

4.3 Results

4.3.1 Plant growth measurements

MANOVA results showed that there were significant differences between treatments in the plant growth measurements taken in the Fall of 2000 ($p < 0.001$, Table 4.2). Between subjects effects were significant for seedling height ($p = 0.009$), needle length ($p < 0.001$), and basal diameter ($p < 0.001$), but not leader height ($p = 0.209$, Table 4.3). Leader height had the smallest observed η^2 for between-subjects effects ($\eta^2 = 0.030$).

At the time of planting (S99), mean total seedling height ranged between 10 cm and 15 cm for the treatment and reference plots (Table 4.1). In both years (1999 and 2000) there were two distinct groupings in seedling height following the trend S+T $\approx$ T < CP $\approx$ B < B+S $\approx$ OL. At the last measurement in the Fall of 2000, CP had a mean total seedling height of 40 cm while S+T and T plots had an average total seedling height of 31 cm. For the CP, this represents an overall gain in height since planting of approximately 30 cm, while the S+T and T plots gained roughly 21 cm in height. Statistically, seedling height of OL lodgepole pine in Fall of 2000 was significantly greater than that of the other plots except B+S (Tables 4.4a and 4.4b).

Mean leader height was measured only in the Fall of 2000. Leader heights were not significantly different between treatments (Table 4.3). OL had the greatest mean leader height (14.9 cm) while B+S had the lowest (8.4 cm, Table 4.1). All other plots had a mean leader height of approximately 10 cm.

Seedling basal diameter in Spring 1999 ranged from 33 to 39 mm for all treatment and reference plots (Table 4.1). By the Fall of 2000, B+S treatment plots had increased in seedling basal diameter to an average of 51 mm while S+T had the greatest seedling basal diameter at 67 mm: a difference of 16 mm when compared to B+S treatments. The rest of the plots had a basal diameter between 66 and 61 mm. Basal diameter of B+S seedlings was significantly smaller than for all other plots in Fall 2000 (Tables 4.4a and 4.4b). No other pair-wise comparisons were significantly different.

Initially, seedling needle length was between 6.5 and 8.0 cm (Table. 4.1). Needle length decreased for all plots by the Fall of 1999 when measurements were taken after bud set. With the exception of B+S, needle length had not changed appreciably when measurements were taken again in Spring 2000. Statistical analysis of differences in needle lengths measured in Fall 2000 showed that S+T and T treatments were not significantly different from each other in needle length ($p = 0.017$, Table 4.4b), and only T was found to be significantly different in needle length from seedlings planted on a control plot (H_2: T = CP, $p < 0.001$, Table 4.4a). The S+T, OL and B plots had intermediate needle lengths relative to other study plots; needle length ranged from 4.8 to 5.6 cm on these plots (Table 4.1). OL and T produced the greatest mean needle lengths (6.6 and 7.1 cm, respectively) at the end of the measurement period. B+S and B seedlings had the lowest needle length (3.8 cm) in the Fall of 2000. Consequently, B+S and B seedlings were the ones most often found to have significantly different needle lengths from other study plots (Table 4.4b). CP seedlings were found to have significantly shorter needle lengths than OL ($p = 0.016$).

Mean shoot weight was not analyzed statistically. The lowest mean shoot weight, 5.0 g was found on the B+S plots (Table 4.1). Reference plots, B, and S+T treatments had roughly the same shoot weights (averages were between 10.0 and 11.1 g). Highest mean shoot weight was found on the T treatment plots (15.4 g).

Overall, seedling mortality was minimal for all plots (Table 4.1). There were two exceptions for this: CP in the period between S99 and F99 (27.8% seedling mortality) and, most notably, B+S for all time periods (between 23.1 and 41.0% seedling mortality). Al l plots besides CP (S99-F99) and B+S (all time periods), had a maximum seedling mortality rate of 5.6%.

4.3.2 Foliar nutrient status

Statistical analysis of foliar nutrient status was not conducted, hence any trends or differences referred to in this section were not substantiated statistically.

4.3.2.1 Selected macronutrients (Total C, N, P, K, Mg, and Ca)

In foliar C content there was virtually no change between years or treatments (Table 4.5). Even including the pre-planting seedlings, all observed values ranged from only 46 to 48 %C.

Biosolid-treated plots had a higher total foliar N than tillage-treated and reference plots, there was a wider range in foliar N concentration in 1999 than in 2000, and tillage-treated and reference plots increased in foliar total N in 2000 (Table 4.5). As a result of the increase in foliar N on tillage-treated and reference plots in 2000, there was very little difference between plots in foliar N in 2000. The range in total foliar N in 1999 was from 0.84% to 1.49% for study plots while in 2000, the range was from 1.23% to 1.45%.

Except for B+S and CP, foliar P levels were higher in 2000 than in 1999 (Table 4.5). The decrease from 1999 to 2000 for B+S and CP was approximately 31 and 13%, respectively. For all other plots, the increase from 1999 to 2000 was between 20 and 30%. In 1999, B+S had the highest foliar P content (1.78 mg/g) while all others had amounts between 0.99 and 1.21 mg P/g. In 2000, plots had a smaller range in foliar P, with the highest value observed coming from seedlings in OL (1.57 mg P/g) and the lowest from CP with 0.93 mg P/g. The patterns of highest to lowest foliar P per plot was very different between years:

1999: B < tillage-treated ≈ CP < OL < B+S
2000: CP < T ≈ biosolid-treated < S+T < OL

Foliar K was highest in needles of seedlings on B+S in 1999 (6.02 mg K/g) (Table 4.5). B+S was the only plot with higher foliar K in 1999 than in 2000. The range in increase of foliar K between 1999 and 2000 was wide (from 8% to 47%). Tillage-treated plots had the greatest increase from 1999 to 2000. In 1999, tillage-treated plots had the lowest foliar K (3.63 and 4.07 mg K/g for S+T and T, respectively), while in 2000, S+T and T had 4.30 and 5.98 mg K/g, respectively. Relative lowest to highest foliar P concentrations for the study plots were very different for each year:

1999: S+T << T < B << CP < OL < B+S
2000: B << B+S ≈ S+T < CP < T < OL

CP and B+S had higher foliar Mg in 1999 than in 2000, unlike the rest of the study plots where foliar Mg was higher in 2000 (Table 4.5). CP and B+S also had the highest observed foliar Mg in 1999 (1.32 and 1.43 mg/g, respectively). Lowest observed foliar Mg in 1999 was from B with 1.09 mg/g. In 2000, the range of in foliar Mg was 1.12 (B+S and OL) to 1.54 mg/g (B). Trends in relative foliar Mg content were similar in 1999 and 2000:

1999: B ≈ OL ≈ S+T < T < B+S < CP
2000: B+S = OL < S+T = CP < T < B

Plots which had higher foliar Ca in 1999 were B+S, S+T, T, and CP; B and OL had higher foliar Ca in 2000 (Table 4.5). These shifts produced very different patterns in relative Ca concentration:

1999: OL < B ≈ CP < T < S+T < B+S
2000: CP < T < S+T = OL < B+S < B

B+S, S+T, T, and CP had a decrease in foliar Ca of approximately 15 to 28% from 1999 to 2000, while the increase from 1999 to 2000 for B and OL was around 40%. The range in concentrations in 2000 was smaller than that observed in 1999. In 1999, foliar Ca ranged from 1.70 mg/g (OL lowest) to 3.77 (B+S highest). In 2000, the range was from 1.70 to 3.05 mg Ca/g (CP and B, lowest and highest, respectively).

4.3.2.2 Selected micronutrients (Cu, Zn, Fe, and Mn)

Needles taken from seedlings in biosolid-treated plots had some of the higher observed values for foliar Cu in 1999 (12.01 and 8.45 μg/g for B+S and B, respectively), but the amount of foliar Cu for these plots decreased between 1999 and 2000 by approximately 40% (Table 4.5). For all other study plots, the amount of foliar Cu increased in 2000. The amount of increase ranged from 9% (CP) to as high as 71% (T). OL and CP had the lowest foliar Cu levels in 1999 and 2000. For the reference plots, the range of observed foliar Cu for both years and plots of just 3.5 to 4.8 μg/g while all other study plots had a range of 4.73 to 12.97 μg/g for both years. Comparison of relative foliar Cu concentrations had few changes in placement of treatment plots between 1999 and 2000:

1999: OL ≈ CP < T < B ≈ S+T < B+S
2000: CP < OL < B < B+S < T << S+T

B+S, B, T, and OL had dramatic changes in foliar Zn between 1999 and 2000 (Table 4.5). For B, T, and OL, the increase in foliar Zn was between 60 and almost 200%, while B+S had a decrease in foliar Zn of 59%. The range in concentration was slightly greater in 1999 than 2000; ranges were 15.65 to 76.98 μg Zn/g and 23.94 to 67.13 μg Zn/g for 1999 and 2000, respectively (all plots). The pattern of plots with lowest to highest foliar Zn was highly changed between 1999 and 2000:

1999: B < CP ≈ T ≈ OL < S+T << B+S
2000: CP < B+S < T < B < S+T << OL

Foliar Mn concentrations showed no definite trends. S+T and OL had large increases in foliar Mn (i.e., S+T had 157 and 485 μg Mn/g in 1999 and 2000, respectively; Table 4.5). Meanwhile, others had substantial decreases such as B+S where needles had 557 μg Mn/g in 1999 and only 150 μg Mn/g in 2000. CP and T had very little change between 1999 and 2000 (i.e., CP had roughly 140 μg Mn/g in both years). These variations produced very different patterns in relative foliar Mn for the two years:

1999: CP < S+T < B ≈ OL < T << B+S
2000: CP ≈ B < B+S << T << OL < S+T

Foliar Fe concentrations were also erratic and relative Fe foliar concentrations reflect this variability (Table 4.5):

1999: OL ≈ S+T < CP << B+S < B < T
2000: OL < B < B+S << tillage-treated << CP

Biosolid-treated and T plots had higher foliar Fe in 1999. S+T, OL and CP had higher foliar Fe in 2000. The greatest difference between years was obtained on S+T where needle samples had 42 μg Fe/g in 1999 and 120 μg Fe/g in 2000. The smallest difference between years was on the other tillage-treated plot, T, with 202 and 192 μg Fe/g in 1999 and 2000, respectively.

4.3.2.3 Other elements (Na, Al, Ni, Cr, and Cd)

All plots had higher foliar Na in 2000 (Table 4.5). The range of foliar Na was far higher in 2000 (602 to 1259 μg Na/g for CP and S+T, respectively) than in 1999 (154 to 444 μg Na/g for OL and CP, respectively. The amount of increase in foliar Na from 1999 to 2000 ranged from about 36 to 663% (CP and OL, respectively), hence the patterns of lowest to highest foliar Na per plot were very different for the two years:

1999: OL < T < S+T << B < B+S < CP
2000: CP = B+S < T < B < OL < S+T

Changes in foliar Al over time were erratic (Table 4.5). B+S had higher foliar Al in 1999 than in 2000 (738 and 223 μg Fe/g, respectively). B stayed approximately the same between 1999 and 2000 with 232 and 236 μg Fe/g, respectively. All other plots had an increase in foliar Al in 2000. The rate of increase was between 181% (T) and 842% (S+T). Ranking of foliar Al concentrations between study plots reflected these large shifts:

1999: S+T << T < CP < OL < B << B+S
2000: biosolid-treated << T << CP < S+T < OL

Ni, Cr, and Cd were below detection limits in HNO_3-H_2O_2 foliage digests.

4.3.3 Soil solution composition

4.3.3.1 Statistical analysis

The main effects Year and Treatment were found to have significant differences between groups in the linear combination of pH, inverse Na, P, square root K, and log Ca calculated by MANOVA, but the interaction of Year and Treatment did not (Table 4.6). The η^2 of Year x Treatment (0.120) was approximately one-third that of Treatment (0.342). Year had an even higher η^2 than Treatment (0.458). Results of the between-subjects tests (Table 4.7) will be given in the sections that follow, as will results of the planned and post-hoc comparisons (Tables 4.8a and 4.8b).

4.3.3.2 pH and soil moisture content

Means for pH were found to be significantly different between Treatment groups while no difference was found for Year (Table 4.7). The η^2 of pH was the lowest η^2 within Treatment to be found statistically significant ($\eta^2 = 0.270$). The pH of soil solution from biosolid-treated plots was between 7.2 and 7.5 in 1999 while all other plots had soil solution pHs between 5.6 and 6.6 (Table 4.10). In 2000, B+S had the lowest soil solution pH (6.17) while the soil solution of B had the highest (6.81). Other plots all had a soil solution pH of 6.4 to 6.5 in 2000. However, these comparisons were not found to be significant (Tables 4.8a and 4.8b). The only paired comparisons found to be significant were those comparing biosolid-treated and control plots (B+S and CP being the exception). For a visual summary of the subjective trends:

1999: OL < CP < S+T < T < B+S < B
2000: B+S < OL ≈ tillage-treated ≈ CP < B

Results presented in Table 4.11 illustrate part of the reason why it was difficult to obtain samples for soil solution analysis in 2000. Soil samples for biosolid-treated plots appear to have been far more moist in 1999 (statistical analysis was not conducted on %MC). B soil samples had 123% moisture in 1999 and only 75% moisture in 2000. Although the difference for T and OL was not as dramatic, percent moisture levels were still higher in 1999 than 2000. For example, T had 19% moisture in 1999 and 12 % moisture in 2000. The one oddity was CP: while percent moisture was reduced in 2000 (82% moisture in 1999 versus 11% moisture in 2000), it was still possible to obtain four soil solution samples from CP soil. Despite having a moderate %MC in 2000 (23%), only half of the soil solution samples obtained from OL were of sufficient volume for analysis by ICP. The pattern of plots (not statistically generated) which had the least and greatest %MC was somewhat changed between 1999 and 2000:

1999: tillage-treated < OL << CP << biosolid-treated
2000: CP < tillage-treated < OL < biosolid-treated

4.3.3.3 Selected macronutrients (P, K, Mg, and Ca)

Mean soil solution P was far higher in 1999 than in 2000, but the major patterns present in 1999 were still present in 2000 (Table 4.9a). Planned and post-hoc comparisons of plots for soil solution P were non-significant (Tables 4.8a and 4.8b), however, and the following observations cannot be confirmed objectively: tillage-treated plots had lower soil solution P than reference plot plots, and biosolid-treated plots had the highest soil solution P. For a visual representation:

1999: S+T < T < CP ≈ OL < B+S < B
2000: tillage-treated < OL < CP < biosolid-treated

To illustrate the difference between years: B+S had a soil solution P concentration of 2.02 mg P/L in 1999 and 1.28 mg P/L in 2000. T had the greatest change in soil solution P with 1.60 and 0.27 mg P/L in 1999 and 2000, respectively. The difference between years were significant (Table 4.7) and P had the highest η^2 within year (0.403) but further statistical analysis as to which plots had a difference for Year was not possible. The η^2 of Treatment for P was low (0.311) relative to the highest η^2s observed for Treatment, which is in keeping with the fact that no pair-wise comparisons were significant for P despite the between subjects effect of Treatment being significant (p = 0.013).

The solution concentration of K decreased between 1999 and 2000 (with the exception of OL, Table 4.9a) and the difference between years was significant (p = 0.006, Table 4.7). CP had the greatest decline in soil solution K between 1999 and 2000 (8.59 and 2.92 mg K/L in 1999 and 2000, respectively). What remained similar between 1999 and 2000 was the fact that tillage-treated plots had lower soil solution concentrations of K than did the biosolid-treated plots and that B+S had lower soil solution K than B, as seen below:

1999: tillage-treated < OL << B+S < CP << B
2000: CP < tillage-treated < B+S < B << OL

However, using $\alpha = 0.0102$, Treatment was not significant in between-subjects comparisons (p = 0.013, Table 4.7), despite the fact that the η^2 of square root K in Treatment (0.270) was very close to that of pH, which was found statistically significant (pH $\eta^2 = 0.230$).

There were no consistent trends between 1999 and 2000 as to which year had the higher concentration of soil solution Ca (Table 4.9a). The lack of observable differences between years in soil solution Ca was reflected with a non-significant p-value for Year (Table 4.7). Treatment, however, was found to be significant for log Ca and its η^2 for Treatment (0.855) was the largest in the between subjects analysis. Biosolid-treated areas were found to have significantly higher soil solution Ca than other study plots (Table 4.8b) as biosolid-treated plots always had concentrations of greater than 200 mg Ca/L while all other study plots had less than 26 mg Ca/L (Table 4.9a). OL was identified as being significantly lower than all other study plots in soil solution Ca (Tables 4.8a and 4.9a). There were no consistent patterns between years or experimental plot types regarding seeding. Here are the relative (subjective) trends for soil solution Ca:

1999: OL $<$ S+T $\approx$ OL $<$ T $\ll$ B+S $<$ B
2000: CP $<$ S+T $<$ T $<$ OL $\ll$ B+S $\ll$ B

Trends for soil solution Mg were very similar as to those found in soil solution Ca (Table 4.9a). Trends for Mg were as follows:

1999: OL $<$ S+T $<$ CP $<$ T $\ll$ B+S $<$ B
2000: CP $<$ S+T $<$ T $<$ OL $\ll$ B+S $<$ B

There was no consistent decline or increase in soil solution Mg concentration between 1999 and 2000, yet biosolid-treated plots always had the highest concentration of soil solution Mg. Biosolid-treated plots had no less than 49 mg Mg/L while all other study plots had no greater than 14 mg Mg/L. In both years, B+S had less Mg in soil solution than did B. These interpretations were not verified by statistical analysis.

4.3.3.4 Selected micronutrients (Cu, Zn, Fe, and Mn)

Micronutrient concentrations in soil solution were statistically analyzed, hence the following generalizations regarding differences between plots and years were subjective.

Soil solution Cu concentrations dropped up to 83% between 1999 and 2000 (Table 4.9b). Tillage-treated plots and CP had the greatest drop. For example, S+T had 0.014 and 0.070 mg Cu/L in 1999 and 2000, respectively. OL and biosolid-treated plots had soil solution Cu levels reduced by at most 60% between years. As a result of these changes, the pattern of which plots had greatest and least soil solution Cu was very different in 1999 and 2000:

1999: OL < S+T < T < CP << biosolid-treated
2000: S+T < CP < OL < T < B < B+S

Decreases in Zn between 1999 and 2000 were relatively consistent across plots with the range in decrease being from approximately 63 to 81% (Table 4.9b). Hence, trends in Zn concentration are very similar for 1999 and 2000:

1999: OL < S+T < B+S < B < T < CP
2000: OL < S+T < B << B+S = CP =T

The highest observed mean soil solution Zn concentration in 1999 was obtained from CP with 110.80 μg/L (Table 4.9b). The lowest in 1999 was the OL with 48.75 μg Zn/L. The highest and lowest concentrations of Zn in soil solution in 2000 were 9.32 μg/L (OL) and 22.55 μg/L (both T and CP).

CP had very high (although not the highest in 1999) soil solution Fe levels relative to other study plots with greater than 20 mg Fe/L in 1999 and 2000 (Table 4.9b). Unlike all other study plots, CP had an increase in soil solution Fe levels between 1999 and 2000. The decrease in soil solution Fe for plots other than CP was between approximately 67 and 85%. Biosolid-treated plots had less than 2 mg Fe/L in both years while tillage-treated and reference plots had more than 15 mg Fe/L in 1999 and between 1.99 and 32.50 mg Fe/L in 2000. Nevertheless, patterns of relative soil solution concentration were fairly stable between 1999 and 2000:

1999: B+S < B << OL < S+T < CP < T
2000: B < B+S < OL << S+T << T << CP

Reduction in soil solution Mn was greatest for B and OL with a decline of approximately 93 and 98%, respectively (Table 4.9b). For example, in 1999 OL had 1.41 mg Mn/L and only 0.02 mg Mn/L in 2000. CP had an increase in soil solution Mn with 0.39 and 1.15 mg Mn/L in 1999 and 2000, respectively. B+S and tillage-treated plots had declines in soil solution Mn of up to 80%. Similar to what was observed in soil solution Cu, these changes created patterns of least to greatest soil solution Mn concentration which were very different for 1999 and 2000:

1999: CP < B+S <B < S+T < T < OL
2000: OL < B < B+S < tillage-treated << CP

4.3.3.5 Other elements (Na, Al, Ni, and Cd)

Na concentrations in soil solution were the only means in this section for which statistical analysis was conducted.

Concentration of Na in soil solution was highest on biosolid-treated plots and there was no consistency as to which year had the higher concentration of soil solution Na (Table 4.9b). In both years, B had higher amounts of Na than did B+S. Tillage-treated and reference plots had different relative rankings in soil solution Na for each year:

1999: OL < T < S+T < CP < B+S < B
2000: CP < OL < tillage-treated << B+S << B

Not surprisingly, Year was not found to be significant for inverse mg Na/L ($p = 0.832$) while Treatment was found to be significant ($p < 0.001$, Table 4.7). The η^2 for soil solution Na associated with Treatment was 0.724, the second-highest η^2 for Treatment. In planned comparisons it was found that tillage-treated areas were not significantly different from CP ($p > 0.066$), S+T was significantly higher in soil solution Na than OL ($p = 0.031$) while T was not ($p = 0.115$), and B+S and B were not significantly different from each other ($p = 1.000$) but they did have significantly higher soil solution Na than all other experimental plots ($p < 0.014$, Tables 4.8a and 4.8b).

Al concentrations in soil solution had the same relative pattern of greatest to least soil solution Al in 1999 and 2000, despite decreases of 30 to 88% between 1999 and 2000 (Table 4.9b):

1999: B+S < B << OL < S+T < T < CP
2000: B+S ≈ B < OL < S+T << T << CP

Biosolid-treated plots had just over 1 mg Al/L in 1999 and 0.2 mg Al/L in 2000. For all other study plots, soil solution Al ranged from 13 to 29 mg/L in 1999 and 2 to 20 mg/L in 2000.

Soil solution concentrations of Cr had the same relative distribution patterns as Al between 1999 and 2000 despite unequal reductions in soil solution Cr on the various plot types (Table 4.9b). Subjective trends for Cr were as follows:

1999: B+S < B << OL << S+T < CP < T
2000: B+S < B < OL << S+T << CP < T

Biosolid-treated plots had less than 19 mg Cr/L in 1999 and between 1 and 5 mg Cr/L in 2000 (Table 4.9b). Tillage-treated plots and CP had more than 60 mg Cr/L in 1999 and between 16 and 42 mg Cr/L in 2000.

Reduction in soil solution Ni between 1999 and 2000 appears to have been remarkably consistent (Table 4.9b). All plots only had between 1 and 4 % of the soil solution Ni in 2000 that was found in 1999. There were a few changes in the pattern of relative soil solution Ni abundance compared across plots:

1999: OL < B+S = S+T < B ≈ OL < CP < T
2000: OL = S+T < biosolid-treated < CP < T

All plots had less than 4 μg Ni/L in 2000, while in 1999 the maximum observed mean soil solution Ni concentration was obtained from T with 105 μg/L and the lowest was the OL with 38.83 μg/L.

Cadmium levels in soil solution were very close for all plots in 1999 (Table 4.9b). The spread between highest and lowest soil solution concentration of Cd in 1999 was between 9 and 12 μg/L. In 2000, soil solution Cd levels were below detection limits. The trend for plots in lowest to highest soil solution Cd levels was as follows:

1999: S+T < B+S < B < OL = CP < T

4.3.4 Relationships between foliar nutrient status and soil solution composition

Statistical analysis of the relationship between foliar nutrient status and soil solution nutrient status was not conducted, hence care was taken to not refer to any of the observations made in the following section as 'correlations.' Analysis of correlations could not be conducted because the sample size of foliar nutrient status was only one aggregate sample per plot.

4.3.4.1 Selected macronutrients (P, K, Mg, and Ca)

Despite soil solution concentrations of P that ranged from 1.27 to 2.69 mg/L in 1999, foliar P concentrations were below 1.21 mg/g for all plots, with the exception of B+S (Figure 4.1). In 2000, although soil solution levels of P were much lower (maximum of 1.28 mg/L on B+S), the range in foliar P was of approximately the same magnitude as in 1999.

Were we to ignore B for 1999, then there would have been a positive relationship between foliar K and soil solution K (Figure 4.2). This pattern does not reappear in 2000.

Soil solution concentrations of Mg and Ca fell into two distinct groups in 1999 and 2000. For soil solution Mg, tillage-treated and reference plots had < 15 mg Mg/L, and biosolid-treated plots had > 45 mg Mg/L. Soil solution Ca was < 50 mg/L for tillage-treated and reference plots, and > 200 mg/L for biosolid-treated plots. Foliar Mg and Ca concentrations did not fall into the same groupings, hence Figures 4.3 and 4.4 do not reflect a relationship between foliar and soil solution Mg concentrations. There was one exception to this, however. In 2000, higher Ca concentrations on B+S and B in soil solution were coupled with higher foliar Ca concentrations.

4.3.4.2 Selected micronutrients (Cu, Zn, Fe, and Mn)

There was a positive relationship between Cu concentrations in foliage and in soil solution in 1999 (Figure 4.5). However, this relationship did not reappear in 2000. In 2000, although B and B+S had the highest soil solution concentrations, the foliar concentrations of Cu for these plots were on par with the majority of the other study plots.

While in 1999 foliar Zn concentrations were unchanged by increasing concentrations of soil solution Zn, in 2000 there was a negative relationship between foliar and soil solution Zn concentrations. For example, OL had the highest foliar Zn in 2000 (67 μg/g) but the lowest soil solution Zn (9 μg/L).

It is possible to state that there was a lack of parallel between foliar and soil solution Fe concentration in 1999, however if T were ignored, the relationship would be a negative correlation (Figure 4.7). The opposite was true in 2000: for 2000, there was a positive correspondence between the amount of Fe in seedling needles and the amount of Fe in soil solution (Figure 4.7). This is illustrated by contrasting B+S, B, and OL with T: B+S, B, and OL all had soil solution concentrations of less < 5 mg Fe/L and < 100 μg Fe/g while T had almost 17 mg Fe/L in soil solution and 202 μg Fe/g in seedling needles.

Mn foliar concentrations seemed unrelated to soil solution Mn concentrations in both years (Figure 4.8). For example, in 2000, OL and S+T had very high foliar Mn concentrations (477 and 484 μg/g, respectively) but soil solution concentrations of Mn were on par with the majority of other study plots.

4.3.4.3 Other Elements (Na and Al)

Although foliar and soil solution Na concentrations had a loose correspondence in 1999, there was little association between foliar and soil solution Na levels in 2000 (Figure 4.9). In both years, biosolid-treated plots had the highest amount of Na in soil solution, but only in 1999 did they also have elevated foliar Na levels.

Very high foliar Al levels were not connected with high soil solution Al concentrations (Figure 4.10). For example in 2000, S+T and OL had approximately 2 mg Al/L in soil solution and in needle tissue, > 700 μg Al/g. For the same year, CP had > 20 mg Al/L in solution and only 624 mg Al/g in the foliage of seedlings on that plot.

4.4 Discussion

4.4.1 Seedling growth

B+S seemed to have taller seedlings than all other plots (except OL) in fall of 2000, however this difference was not statistically significant. In basal diameter and needle length, B+S seedlings were found to be significantly smaller than seedlings from other study plots. The highest seedling mortality was also found on B+S plots. Lodgepole pine has a low shade tolerance (Pfister and Daubenmire 1973) and density of grass species was high, therefore it is reasonable to conclude that B+S seedlings were suffering from intense competition with the grasses and from the shade the grasses created.

On the basis of planned and post-hoc comparisons of seedling growth measurements, seedlings from B appear to be doing as well as seedlings on tillage-treated plots and the CP plot. OL seedlings had the greatest total height (a statistically significant difference), while seedlings from T had the greatest basal diameter (albeit not significantly greater than all plots), needle length, and shoot weight (subjective differences rather than statistically verified). It should be noted, however, that the seedlings were only measured for two growing seasons and these trends may not be maintained in the future.

Kranabetter and Osberg (1995) found that, in comparison to landing decompaction alone, growth of lodgepole pine seedlings was best in areas where topsoil had been respread in combination with landing decompaction, so perhaps it is not surprising that the growth of seedlings on tillage-treated plots in the present study was not improved over that of seedlings grown on untreated landing. Kranabetter and Osberg (1995) also did not have success in seeding cover crops on their landing reclamation trials (in addition to other treatment application problems). As a result, they could not come to a conclusion regarding whether treatment with seeding a cover crop enhanced seedling growth over decompaction.

Seeding and fertilization treatments of logging roads produced a considerable increase in Douglas fir seedling height over untreated control plots in a study by Carr (1987b). However, the report did not find a statistically significant increase in the height of lodgepole seedlings planted on landing areas treated with tillage, seeding of legumes, and fertilization, even though the mean height of seedlings on untreated landings and treated landings were 36.5 and 43.3 cm, respectively, two years after being planted. In the present study, seedlings planted in tillage-treated plots and untreated landing were all approximately 31 cm tall two years after being planted.

Carr (1987b) concluded that more time was required in order to see whether site nutrient levels would continue to be adequate and whether there would eventually be a response to the improved nutrient levels from seeding a cover crop. In the present study, it does not seem reasonable to suggest that the performance of lodgepole pine seedlings in S+T plots will improve with time relative to untreated landing areas as the cover crop of S+T failed to establish. Conditions favouring germination and establishment of a fallow crop, such as adequate moisture, temperature, and oxygen levels (Bradbeer 1988), are not the same as the factors which are involved in seedling growth, such as adequate irradiance, nutrient supply, and abrasion by touch or wind (Lambers et al. 1998); however, it is unlikely that the soil condition of S+T plots (and therefore the growth of seedlings on S+T plots) will be improved in the future over that of the untreated landing plot without further human or natural action.

When comparing lodgepole pine seedling growth on- and off-landing, Carr (1987a) found that seedlings planted on-landing were far smaller. In 6 years, the seedlings of summer- and winter-constructed landings were 54 and 72% of the height of seedlings growing off-landing. After 11 years, the seedlings of summer- and winter-constructed landings were only 42 and 38% as high as those growing off-landing. Only 2 growing seasons had past for the lodgepole pine seedlings measured in the present study and already CP seedlings are just 67% as tall as the OL seedlings (a statistically significant result).

4.4.2 Foliar nutrient status

A review done by Ballard and Carter (1986), proposed foliar nutrient levels which could be considered indicators of adequacy of plant nutrition. In that review, the authors stipulated that thresholds may not adequately represent the demands of rapidly growing seedlings, and for micronutrients, that the ranges presented were arrived at from studies of a variety of species (the ranges for macronutrients were specific to lodgepole pine). The following section includes evaluation of the foliar nutrient status of seedlings according to the guidelines of Ballard and Carter (1986) and the cautions they stipulated in their review in interpreting thresholds should be kept in mind when reading this section.

4.4.2.1 Selected macronutrients (N, P, K, Mg, and Ca)

When the seedlings were planted, they had foliar N concentrations of 1.95% (Table 4.5), therefore the foliar N levels of the Fall of 1999 represent a considerable drop in foliar nutrient status. By the onset of dormancy in 1999, all plots except the biosolid-treated plots (which had foliar N levels which would be characterized as slight moderate deficiency for B and adequate for B+S) had a foliar N status that would be considered very severely deficient (< 1.05 %N) according to guidelines presented by Ballard and Carter (1986). In 2000, seedlings in biosolid-treated plots still had a foliar N status of slight moderate deficiency (1.20 to 1.55 %N), and all other plots had improved to slight moderate deficiency as well (Ballard and Carter 1986).

Foliar N content of seedlings in B plots was almost at the level considered adequate (Ballard and Carter 1986), which indicates that biosolid treatment enhanced seedling foliar N status over that of all other treatment and control plots. It is surprising that the N status of B+S seedlings was not substantially lower than that of other plots in 2000, given the fact that the seedlings looked distressed and had heavy competition from grasses. B+S seedlings may have been surviving by internally translocating N (Barber 1995) already present at the time of planting. The very low shoot weight of seedlings from B+S might have made it possible for them to subsist on translocated N, given that an increase in biomass was not creating a dilution effect (Barber 1995). Unfortunately, it was not possible to conclude from the information collected how much N the B+S seedlings were obtaining from the soil.

It is interesting that the foliar N status of CP was the second-highest observed in 2000. Conclusions in a study of the effects of landing construction on soil properties and forest productivity indicated that foliar N status of six year-old lodgepole pine seedlings was not reduced because the increased mass of the soil was providing adequate N at the time, but that as the compacted soil restricted the rooting zone of trees, a deficiency of foliar N would appear in three to five years (Carr 1987a). This principle may also have been active for CP seedlings involved in this study. Foliar N status of CP seedlings may also have been the result of the growth of clover that was naturally regenerating in the plot. If the N status of CP seedlings was due to N fixation by the clover, then the foliar N status of CP should continue to be sufficient. If it was due to factors mentioned by Carr (1987a), the prognosis for the N status of the seedlings may echo that voiced by Carr (1987a).

Samples of foliage taken in the fall of 2000 from experimental plots showed a slight deficiency for P (0.12 to 0.15 %P) while OL had adequate P (> 0.15 %P) and CP was moderately P-deficient (0.09 to 0.10 %P), according to guidelines presented by Ballard and Carter (1986). All plots, with the exception of B+S and CP, had an increase in foliar P between 1999 and 2000. As was true for foliar N, B+S seedlings were probably obtaining little P from the environment and were subsisting by translocating P (Barber 1995) provided while seedlings were in the nursery. In the same study by Carr (1987a) discussed above regarding foliar N, it was concluded that the increased mass of the soil was not sufficient to offset the loss of P from the site by removal of the forest floor. This provides an explanation as to why CP seedlings decreased in foliar P while increasing in foliar N in the present study. Tillage-treated plots probably increased in foliar P because some sources of more available P were brought to the soil surface by tillage. These sources of more available P will likely be depleted in a short period of time, after which the foliar P status of the seedlings in the tillage-treated plots will decline.

Biosolid-treated plots had the poorest foliar K status in 2000: approximately a slightly-moderately deficient (0.40 to 0.50 %K). All other study plots were possibly slightly deficient (0.50 to 0.55 %K) or better (terminology and thresholds after Ballard and Carter 1986). Foliar K status of B+S was probably higher in 1999 than 2000 due to translocation, as was discussed regarding foliar N and P. Comparing foliar K in 2000 of biosolid-treated plots to tillage-treated and to reference plots indicated that the mineral soil of the tillage-treatment and reference plots is a better source of K than the biosolid-amended soil.

Even unreclaimed control plots studied by Carr (1987a and 1987b) had foliar N, P, and K concentrations which were generally higher than those for any study plot in the reclamation trial investigated herein. Unfortunately, the present study did not use the same soil analysis methods as Carr (1987a and 1987b) and it is not possible to conclude whether soil N, P or K in their study area was substantially greater than those of this study area. Also, any differences between the present study and that of Carr (1987a and 1987b) should not be over-interpreted as it is not possible to predict from two years of seedling growth whether these trends will remain in the future.

All plots had sufficient foliar Ca and Mg with greater than the 0.10 %Ca and 0.10 %Mg thresholds which indicate adequate Ca and Mg nutrition (Ballard and Carter 1986). It is unlikely that Ca or Mg will become limiting in the future.

4.4.2.2 Selected micronutrients (Cu, Zn, Fe, and Mn)

Levels of Cu and Zn in the seedling foliar tissue were well above the levels suggested as representing possible deficiency (4 ppm for Cu and 15 ppm for Zn) by Ballard and Carter (1986). In 2000, only OL came close to having a foliar Fe status of 'low to zero probability of deficiency' (25 to 50 ppm); the rest were well above 50 ppm Fe.

Foliar concentrations of > 25 ppm Mn are considered to present no potential for Mn deficiency (threshold and terminology after Ballard and Carter 1986). Minimum observed foliar Mn in this study was found in the pre-planting trees with 143 μg/g, while the highest was 556 μg/g. For plants which are not considered tolerant or highly sensitive to Mn, the range of Mn in foliar tissues which potentially represents Mn phytotoxicity is 300 to 500 μg/g (McBride 1994), hence it is possible that seedlings in the present study are experiencing stress due to Mn concentrations. Yet, OL had some of the highest foliar Mn levels, therefore if Mn toxicity is present, it is due to site factors not to reclamation treatments.

4.4.2.3 Other elements (Na and Al)

Foliar tissue levels in the range of 50 to 200 μg Al/g are potentially phytotoxic for plants not considered to be tolerant or highly sensitive to Al (McBride 1994). All aggregate samples were well over 50 μg Al/g, including the pre-planting seedlings with 235 μg Al/g. Since even the seedlings direct from the nursery were over the range representing potential phytotoxicity, it is reasonable to conclude that despite being high relative to a generally acceptable range in Al, those seedlings with approximately 200 μg Al/g are not necessarily experiencing Al stress. Also, OL seedlings had the highest of all foliar Al concentrations, suggesting that the high Al levels were not induced by landing reclamation.

4.4.3 Soil solution pH

Although acidification of biosolid-treated soil was not evident (Figures 3.3 and 3.4), there was a clear decrease in the pH of soil solution from biosolid-treated plots between 1999 and 2000. Di- and tri-valent cations dominate the exchange complex of the biosolid-treated plots and these higher valence cations are adsorbed preferentially over H^+ (McBride 1994). Hence, the H^+ generated by nitrification cannot replace the higher charge ions on exchange complexes and the solution, therefore, is acidified rather than the solid phase being acidified. Perhaps over time as the organic matter quality on the site decreases, nitrification rates will decrease, H^+ will leach from the profile, and base cations will begin to move into soil solution, reaching a new equilibrium having a solution pH close to that of the total soil.

Kraske and Fernandez (1993), at the end of their study period, also had a soil solution pH which was lower than that of the total soil, however the difference in their study was only about 0.5 pH units. Solution pH results obtained by Kraske and Fernandez for papermill biosolid-treated plots were also more erratic than those found in the present study; sometimes being higher or lower than the forested and harvested reference plots.

4.4.4 Soil solution composition

4.4.4.1 Selected macronutrients (P, K, Mg, and Ca)

Hue et al. (1988) conduced a four-week greenhouse study using three different soils and three municipal biosolid loading rates. Their results found that the amount of P in solution increased with increased biosolid loading rates, but that the degree of the increase depended on the soil type. They found soil solution concentrations of 0.05 mg P/L or less for unamended soil and up to 1.85 mg P/L at the highest biosolid loading rates. In the present study, soil solution P for tillage-treated and reference plots was generally higher than that found at the highest loading rates by Hue et al. (1988) and the biosolid-treated plots had soil solution P either on-par with or substantially greater than their amended soils even though the loading rate was less than that used by Hue et al. (1988). This study used 70 Mg/ha municipal biosolids while Hue et al. (1988) applied up to 180 Mg/ha, however the P concentration in their biosolids may have less than half of that in the biosolids used in this study (see Table 3.4).

The amount of Ca in soil solution for two growing seasons after pulpmill waste application found by Kraske and Fernandez (1993) declined considerably to concentrations almost on par with their reference forested and harvested plots. Although the amount of Ca in solution from biosolid-treated plots in the present study fluctuated by as much as 70 mg/L between years, the amounts of Ca in solution on the tillage-treated and reference plots was considerably lower than that of the biosolid-treated plots.

Results of the present study do not match those of Kranske and Fernandez (1993) for Mg concentration in soil solution. Kraske and Fernandez (1993) found the highest concentrations of Mg in solution one month following papermill biosolid application, after which Mg concentration in soil solution decreased. For biosolid-treated plots in the present study, Mg concentrations in soil solution remained the same or increased from 1999 to 2000.

4.4.4.2 Selected micronutrients (Cu, Zn, Fe, and Mn)

Cu, Zn, and Fe in soil solution were below detection limits (< 0.01 mg/L) at the end of the four-week study by Hue et al. (1988). There are two potential reasons why Hue et al. (1988) had lower Cu, Zn, and Fe in soil solution that was found in the present study. Firstly, the amount of Cu, Zn and Fe in the biosolids used by Hue et al. (1988) appears to be lower than those applied in this study (see Table 3.4). Prince George municipal biosolids are, in fact, know for their high Cu content (Bulmer, pers. comm.. 2003). Secondly, they used lower application rates, and the primary clarifier waste added in the present study may have provided a greater source of organic ligands to bring these metals into solution in comparison to the municipal biosolid application used by Hue et al. (1988). However, these conclusions may be overstating the significance of biosolid application in causing the differences in results between this study and that of Hue et al. (1988) since the amount of Cu, Zn, and Fe in the soil solution of tillage-treated and reference plots for this study was even higher than the treated soils of Hue et al. (1988).

Zn concentrations in soil solution of leaching columns packed with primary pulp mill sludge alone or mixed with one of three different soil horizons tended to decline slowly over a series of six leachings in a study conducted by Xiao et al. (1999). It may be that the tendency for Zn in solution to decline found by Xiao et al. (1999) will be repeated in this study since Zn levels on all of the experimental plots decreased a great deal between 1999 and 2000. However, reference plots also had a decrease in Zn concentration, hence the present results may be only a reflection of natural variability in soil solution Zn levels for this site.

It is not surprising that biosolid-treated plots have far less Fe in solution than other plots: they have 10-20 mg/g less total Fe than other study plots and the higher pH of the biosolid-treated plots will cause more Fe to be precipitated in biosolid-treated plots than in other study plots. The high Fe concentration in soil solution from CP has no obvious cause. In 1999 a reducing environment may have been present, but this explanation is not satisfactory for the 2000 data because the %MC was far lower. The pH of CP was not substantially different from that of the tillage-treated plots therefore the difference between tillage-treated and CP in soil solution Fe concentration in 1999 cannot be attributed to pH. Fe does form complexes with organic ligands in solution, however this explanation is also inappropriate to explain why Fe in soil solution of CP was elevated in 2000, given that there had been no disturbance of or additions to the soil of the plot.

As with P in soil solution, Hue et al. (1988) found that the amount of Mn in solution increased with increased biosolid loading rates, and that the degree of the increase depended on soil type. They found this result to be surprising since Mn solubility is highly controlled by pH and concluded that the increasing amounts of Mn in solution regardless of changes in pH must have been be due to adsorption on dissolved organic compounds. In the present study, Mn concentration decreased in soil solution for all plots except CP between 1999 and 2000, regardless of whether pH decreased, increased, or remained approximately the same. Hence, for the present study, Mn concentration in soil solution cannot be speculatively connected to differences in pH or amounts of dissolved organic ligands.

4.4.4.3 Other elements (Na, Al, Cr, Ni and Cd)

Biosolid-treated plots had higher Na concentrations in soil solution in 2000 than in 1999, which is in keeping with results from Kraske and Fernandez (1993) who also had found that Na increased in the second growing season after primary and secondary clarifier waste had been added to two forest soils. Their results also show small increases and decreases in soil solution Na from reference forested and harvested plots, but the fluctuations were very mild in comparison to maximum and minimum Na concentrations on biosolid-treated plots, which is also consistent with the results presented herein: tillage-treated and reference plots had solution Na concentrations that were much lower than biosolid-treated plots. Results where biosolid-treated soil had large increases and decreases in soil solution Na were also presented in a leaching column experiment done by Xiao et al. (1999), who found that Na in solution decreased with the first five leachings and then began to increase for the final two leachings, regardless of whether the column contained primary pulp mill sludge alone or mixed with one of three different soil horizons.

Concentrations of Ni and Cd for Hue et al. (1988) were below detection limits in the soil solution. The amount of Cd in the present study was also below detection limits in soil solution in 2000 and it may be that Ni would also be below detection limits in the future given how low concentrations of Ni in solution were in 2000 compared to 1999. This conclusion is confounded, however, by the fact that concentrations of all elements were lower in soil solution in 2000.

4.4.5 Relationships between foliar nutrient status and soil solution composition

Based on comparing trends between plots using lowest to highest concentrations of a given element in soil solution versus in seedling foliage, parallels in tissue and solution concentrations were rare. There were few instances where solution and foliar trends in elemental concentration did coincide. Length of storage before extraction alters soil solution composition (Quian and Wolt 1990). Since soil solution extractions could not all be performed on the same day in this study, perhaps storage effects are interfering with clarity in trends between solution and foliar levels.

Although soil solution concentrations of P and K were lower in 2000, foliar concentrations of these elements are generally higher in 2000. These two elements are translocated by the plant from older tissues to newer tissues (Barber 1995), which could account for their general increase in foliar tissues despite dropping in soil solution concentration. It cannot be concluded at this time that the decline in solution P and K will be permanent and that seedling demand for these nutrients will inevitably outstrip the ability of the soil to provide them.

Perhaps it should not be surprising that relationships were seldom found between soil solution concentrations of an element and the concentration of that element in lodgepole pine needles. Plants have a variety of mechanisms available to them to enhance the availability of limiting nutrients, such as production of chelating agents, high-affinity uptake systems, and mycorrhizal associations (Larcher 1995, Lambers et al. 1998). From that perspective, it may be possible to conclude that although the trees may be stressed by the nutrient deficiencies discussed in 4.4.2, the potential exists for them to continue to survive.

Carr (1987b) also was unable to find statistically significant differences in foliar nutrient levels in response to increased soil nutrient levels. The landing reclamation treatment used by Carr (1987b) included tillage, seeding of legumes, and fertilization. After two years, foliar N of lodgepole pine seedlings was improved to 1.72 %N by treatment, in comparison to untreated landing areas where seedlings had foliar N of 1.68%. Foliar P and K were unchanged by treatment. This was despite improvements in available N, P, and K as a result of landing reclamation.

4.4.6 Potential environmental impacts of biosolid application

Soil solution composition will be compared to the Canadian Water Guidelines for irrigation water and livestock water (Health Canada 1995) to assess possible environmental contamination from sludge application. Evaluating the soil solution composition using the guidelines for drinking water and freshwater aquatic life would be too restrictive to be relevant for evaluation of soil solution concentrations in this forestry application. The Guidelines caution that acceptable limits will change with water hardness, temperature, and pH (depending on the element in question) because a measure of absolute concentration of an element in solution does not necessarily indicate the potential for toxicity of the element or bioavailability.

Amounts of Ca, Cu and Zn in soil solution were below guidelines set for irrigation and livestock waters (Health Canada 1995). In 1999 and 2000, Fe concentrations in soil solution exceeded the 5.0 mg/L Canadian Water Guideline for irrigation water in the tillage-treated plots and CP (Health Canada 1995). OL also exceeded this guideline in 1999. Given that Fe concentration in soil solution of tillage-treated plots decreased in 2000, the high Fe soil solution in 1999 may have been due to a tillage effect. However, if changes in the soil solution of OL represent the natural variability Fe in soil solution in this area, then tillage-treated plots may increase in soil solution Fe again in the future.

Mn concentrations in soil solution were well above the 0.2 mg/L Canadian Water Guideline for irrigation water (Health Canada 1995) for all plots in 1999. In 2000, only T and CP exceeded this limit. Were pH the controlling factor for Mn solubility in this study, then OL would have had higher soluble Mn than the tillage-treated plots in 1999 when soil solution pH of OL was a unit lower than the tillage-treated plots, and OL would have had approximately the same concentration of Mn in solution as the tillage-treated plots in 2000 when the soil solution pH of these plots was equivalent. This supposition holds true for 1999, but in 2000 OL had substantially lower Mn in solution than tillage-treated plots. Perhaps pH is not a major factor controlling Mn solubility for these plots, or perhaps the poor sample size for OL in 2000 is masking the effect of pH.

Al concentration in soil solution of tillage-treated and reference plots in 1999 was substantially above the 5 mg Al/L Canadian Water Guideline for irrigation and livestock waters (Health Canada 1995). In 2000, the Al content of the soil solution for tillage-treated plots and OL had decreased substantially while CP retained elevated levels of Al. As discussed for soil solution Fe, elevated Al in soil solution of tillage-treated plots in 1999 may have been a result of tillage treatment; if so, then the concentration of Al in solution should continue to decline for tillage-treated plots. OL changes in soil solution Al concentration could represent the natural variability of Al in soil solution in this area; if this is the case then tillage-treated plots may increase in soil solution Al again in the future. While a reducing environment in the soil in 1999 may have explained the elevated concentrations of Fe in soil solution, Al is not part of the reduction and oxidation sequence (McBride 1994). Hence, for Al, even fewer potential explanations exist for explaining why soil solution concentration is so high. The pH of the soil is in the range where soluble Al should be at its lowest (McBride 1994), therefore organic ligands bringing Al into solution of Al was the only viable explanation, but this explanation is only suitable for the biosolid-treated and OL plots.

Soil solution concentrations of Cr, Ni and Cd were below the limit for irrigation and livestock waters (Health Canada 1995). In a study by Xiao et al. (1999), Cr concentrations were below detection limits in soil solution after the first leaching of columns packed with primary pulp mill sludge alone or mixed with one of three different soil horizons. Cr concentration in soil solution may fall below detection limits on biosolid-treated plots in the present study, given that the concentrations found in the biosolid-treated plots are far lower than all other plots in 2000.

4.5 Conclusions

Although foliar nutrient status (macronutrients especially) were similar between tillage-treated and biosolid-treat plots in 2000, this does not necessarily represent an equivalency of the treatments over the long term. The fact that there was no luxury uptake of elements may indicate that the decomposition of organic matter is proceeding at a constant rate on biosolid-treated plots and will continue to release nutrients over the long term. Tillage-treated plots have no such storehouse of nutrients to provide the seedlings with when increased growth rates increase the demand for nutrients.

Root competition for elements with high diffusion rates (i.e., sulphate and nitrate) appears at lower root densities than does competition for elements with lower diffusion rates (i.e., P, K, Zn) (Clarkson 1985). If this study were conducted over a longer period of time, it may have been possible to see differences in foliar nutrient status arise between B+S and B as a result of this competition. Instead, B+S likely represented seedling survival by translocation of elements as a result of intense competition more than it reflected biosolid treatment, while B more accurately reflected the effect of biosolid application.

Soil solution concentrations of Fe, Mn, and Al occasionally exceeded Health Canada (1995) guidelines for irrigation and livestock water, however, these infractions were found just as frequently on reference and tillage-treated plots as on biosolid-treated plots. Therefore, the biosolid application rates used in this study do not pose a risk to the environment from these metals.

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Table 4.1 Mean and standard error of plant growth measurements for seedlings from Clear Lake trials. Means within a row with the same letter in their superscript were not statistically different. Only F00 data was statistically analyzed. See section 4.2.5 and Tables 4.4a and 4.4b.

Sampling Time	Plot Identification B+S	B	S+T	T	OL	CP
Mean Seedling Height (cm)*						
S99	13.1(0.77)	13.5(0.57)	10.5(0.57)	10.1(0.57)	10.2(0.64)	14.6(0.83)
F99	27.0(1.00)	23.8(0.56)	20.0(0.79)	20.5(0.78)	26.9(1.29)	23.9(0.79)
S00	29.1(0.73)	24.4(0.56)	21.4(0.78)	21.1(0.74)	27.8(1.25)	24.0(0.80)
F00	36.0(1.50)^{ab}	33.4(1.06)^{a}	31.2(1.31)^{a}	31.1(0.90)^{a}	40.6(1.67)^{b}	32.3(1.34)^{a}
Mean Leader Height (cm)*						
F00	8.4(1.02)	10.9(0.69)	10.6(0.93)	10.8(0.75)	14.9(1.00)	10.3(1.27)
Mean Needle Length (cm)*						
S99	6.5(0.42)	7.5(0.45)	7.1(0.36)	7.3(0.33)	8.0(0.68)	7.4(0.57)
F99	3.8(0.26)	5.8(0.24)	4.3(0.14)	4.4(0.18)	5.7(0.31)	4.5(0.17)
S00	4.2(0.25)	5.6(0.24)	4.1(0.13)	4.2(0.13)	5.3(0.28)	4.3(0.17)
F00	3.7(0.27)^{a}	4.7(0.21)^{ab}	5.6(0.30)^{bc}	7.1(0.33)^{c}	6.6(0.29)^{c}	5.1(0.34)^{b}
Mean Basal Diameter (mm)*						
S99	33(1.0)	33(1.2)	35(1.3)	34(1.2)	39(1.7)	37(1.8)
F99	35(1.2)	44(1.3)	43(1.0)	43(0.9)	43(1.5)	42(1.5)
S00	44(1.1)	48(1.2)	44(0.9)	45(0.9)	47(1.5)	46(1.7)
F00	51(1.8)^{a}	61(1.9)^{ab}	63(1.3)^{b}	67(1.4)^{b}	64(2.8)^{b}	66(1.7)^{b}
Mean Shoot Weight (g)**						
F00	4.99(0.95)	11.09(2.74)	10.93(1.90)	15.43(1.58)	11.10(3.00)	10.03(0.75)
Seedling Mortality (%)***						
S99 to F99	41.0	2.8	2.7	0	5.6	27.8
F99 to S00	40.0	0	2.9	3.0	0	0
S00 to F00	23.1	0	0	0	0	0

* Sample sizes were as follows:
S99: B+S = 39, B = 36, S+T = 37, T = 36, OL = 18, CP = 18
F99: B+S = 37, B = 35, S+T = 34, T = 33, OL = 16, CP = 16
S00: B+S = 39, B = 35, S+T = 37, T = 36, OL = 17, CP = 16
F00: B+S = 24, B = 32, S+T = 34, T = 35, OL = 17, CP = 17

** Sample sizes were six for experimental plots, three for reference plots.

*** Sample sizes were as follows:
S99 to F99: B+S = 39, B = 36, S+T = 37, T = 36, OL = 18, CP = 18
F99 to S00: B+S = 30, B = 35, S+T = 34, T = 33, OL = 16, CP = 14
S00 to F00: B+S = 39, B = 32, S+T = 35, T = 36, OL = 17, CP = 16

Table 4.2 MANOVA table using Pillai's Trace to evaluate effects of landing reclamation on lodgepole pine seedling growth (two growing seasons) on Clear Lake trials based on the variables total height (cm), basal diameter (mm), needle length (cm), and leader height (cm). $\alpha = 0.05^*$.

Source of variation	Hypothesis df	Error df	Pillai's value	$F_{observed}$	Eta squared	Significance
Treatment	12	444	0.603	9.316	0.201	<0.001

* See Table 4.1 for sample sizes.

Table 4.3 ANOVA table for between-subjects effects in lodgepole pine seedling growth (two growing seasons) on Clear Lake trials based on the variables total height (cm), basal diameter (mm), needle length (cm), and leader height (cm). $\alpha = 0.013^*$.

Source of Variation	df	SS (Type III)	MS	$F_{observed}$	Eta squared	p-Value
Treatment						
seedling height (cm)	3	4.52×10^2	1.50×10^2	4.022	0.075	0.009
leader height (cm)	3	87.2	29.1	1.531	0.030	0.209
needle length (cm)	3	1.69×10^2	56.2	26.77	0.350	<0.001
basal diameter (mm)	3	0.38	0.13	15.51	0.238	<0.001
Error						
seedling height (cm)	149	5.56×10^3	37.4			
leader height (cm)	149	2.83×10^3	19.0			
needle length (cm)	149	3.13×10^2	2.10			
basal diameter (mm)	149	1.21	8.14×10^{-3}			

* See Table 4.1 for sample sizes.

Table 4.4a P-values of planned comparisons of lodgepole pine seedling growth measurements for the Clear Lake reclamation trials using Dunnett's method. $\alpha = 0.05$. See Table 4.1 for sample sizes.

Planned Comparison	Variable		
	Seedling height (cm)	Needle length (cm)	Basal diameter (mm)
H_1: S+T = CP	0.953	0.650	0.810
H_2: T = CP	0.923	<0.001	0.982
H_3: B+S = CP	0.183	0.012	<0.001
H_4: B = CP	0.951	0.846	0.253
H_5: S+T = OL	<0.001	0.084	1.000
H_6: T = OL	<0.001	0.551	0.556
H_7: B+S = OL	0.069	<0.001	<0.001
H_8: B = OL	0.001	<0.001	0.737
H_9: CP = OL	0.001	0.016	0.924

Table 4.4b P-values of post-hoc comparisons of lodgepole pine seedling growth measurements for the Clear Lake reclamation trials using Bonferroni for seedling height and leader height, Tamhane's T2 for needle length and basal diameter. $\alpha = 0.008$. See Table 4.1 for sample sizes.

Planned Comparison	Variable		
	Seedling height (cm)	Needle length (cm)	Basal diameter (mm)
H_{10}: B+S = B	1.000	0.179	0.010
H_{11}: B+S = S+T	0.058	<0.001	<0.001
H_{12}: B+S = T	0.042	<0.001	<0.001
H_{13}: B = S+T	1.000	0.564	0.999
H_{14}: B = T	1.000	<0.001	0.338
H_{15}: S+T = T	1.000	0.017	0.629

Table 4.5 Foliar concentration of selected elements in aggregate needle samples of seedlings from Clear Lake trials. Ni, Cr, and Cd were below detection limits.*

Element	Plot Identification						Concentration at Planting
	B+S	B	S+T	T	OL	CP	
P (mg/g)							
1999	1.78	0.99	1.05	1.02	1.21	1.07	1.84
2000	1.22	1.21	1.33	1.22	1.57	0.93	
K (mg/g)							
1999	6.02	4.35	3.63	4.07	5.43	5.10	7.83
2000	5.21	4.71	5.30	5.98	6.24	5.53	
Ca (mg/g)							
1999	3.77	2.13	3.33	2.42	1.70	2.21	2.86
2000	2.78	3.05	2.40	2.04	2.40	1.70	
Na (μg/g)							
1999	365.09	300.46	195.86	172.14	153.90	444.32	212.90
2000	603.20	666.43	1259.18	640.54	1174.25	602.81	
Mg (mg/g)							
1999	1.32	1.09	1.11	1.17	1.10	1.43	1.63
2000	1.12	1.54	1.36	1.45	1.12	1.36	
Mn (μg/g)							
1999	556.77	190.23	157.26	210.12	193.93	143.59	138.38
2000	149.75	144.59	484.61	221.12	477.73	141.74	
Fe (μg/g)							
1999	124.95	161.75	41.92	202.01	43.46	72.81	265.41
2000	93.55	84.88	199.90	192.06	51.20	250.48	
Al (μg/g)							
1999	737.73	232.06	85.21	155.89	215.65	189.22	235.51
2000	226.07	236.36	802.49	439.26	909.34	624.50	
Cu (μg/g)							
1999	12.01	8.45	8.58	4.73	3.65	3.53	15.23
2000	6.70	5.03	12.97	8.11	4.84	3.88	
Zn (μg/g)							
1999	76.98	15.65	31.93	22.19	22.62	21.07	35.39
2000	31.41	37.80	42.10	35.56	67.13	23.94	
Percent N							
1999	1.49	1.30	1.01	0.84	1.01	0.82	1.95
2000	1.34	1.45	1.23	1.37	1.35	1.41	
Percent C							
1999	47.83	47.83	48.27	48.52	47.86	47.39	47.93
2000	48.74	47.89	48.56	48.71	47.91	46.97	

* In each year, sample size was 1 for OL and CP, 2 for B+S, B, S+T, and T.

Table 4.6 MANOVA table using Pillai's Trace to evaluate effects of landing reclmation on soil solution composition of Clear Lake trials, based on the variables pH inverse Na, P, square root K, and log Ca. Units were mg/L for all variables, except pH. $\alpha = 0.05$.*

Source of variation	Hypothesis df	Error df	Pillai's value	$F_{observed}$	Eta squared	Significance
Year	5	37	0.46	6.25	0.458	<0.001
Treatment	15	117	1.03	4.05	0.342	<0.001
Year X Treatment	15	117	0.36	1.06	0.120	0.399

*Sample sizes were: 1999 B+S = 7, B = 8, S+T = 8, T = 8, CP = 4, OL = 4
2000 B+S = 5, B = 5, S+T = 5, T = 6, CP = 1, OL = 4

Table 4.7 ANOVA table for between-subjects effects in soil solution composition of Clear Lake landing reclamation trials. Units were mg/L for all variables except pH. $\alpha = 0.0102$. See Table 4.6 for sample sizes.

Source of Variation	df	SS (Type III)	MS	$F_{observed}$	Eta squared	p-Value
Year						
pH	1	0.528	0.528	2.24	0.052	0.142
inverse Na	1	1.61×10^{-4}	1.61×10^{-4}	0.45	0.001	0.832
P	1	13.38	13.38	27.72	0.403	<0.001
square root K	1	3.07	3.07	8.30	0.168	0.006
log Ca	1	4.39×10^{-2}	4.39×10^{-2}	0.95	0.023	0.335
Treatment						
pH	3	3.58	1.19	5.06	0.270	0.004
inverse Na	3	0.27	9.15×10^{-2}	35.92	0.724	<0.001
P	3	8.92	2.97	6.16	0.311	0.001
square root K	3	4.54	1.51	4.08	0.230	0.013
log Ca	3	11.14	3.71	80.52	0.855	<0.001
Error						
pH	41	9.66	0.24			
inverse Na	41	0.10	2.55×10^{-3}			
P	41	19.79	0.48			
square root K	41	15.18	0.37			
log Ca	41	1.89	4.61×10^{-2}			

Table 4.8a P-values of planned comparisons* for the Clear Lake reclamation trials using the Dunnett method to evaluate differences between treatments in soil solution pH, inverse Na, P, and log Ca. $\alpha = 0.05$. See Table 4.6 for sample sizes

Planned Comparison	pH	inverse Na	P	log Ca
H_1: S+T = CP	0.279	0.162	0.230	0.839
H_2: T = CP	0.274	0.066	0.721	0.953
H_3: B+S = CP	0.082	0.014	0.994	<0.001
H_4: B = CP	<0.001	0.001	0.406	<0.001
H_5: S+T = OL	0.075	0.031	0.460	0.001
H_6: T = OL	0.068	0.115	0.984	<0.001
H_7: B+S = OL	0.012	<0.001	0.751	<0.001
H_8: B = OL	<0.001	<0.001	0.092	<0.001
H_9: CP = OL	0.991	0.001	0.976	0.001

Table 4.8b P-values of post-hoc comparisons* for the Clear Lake reclamation trials using Bonferroni to evaluate differences between treatments in soil solution inverse Na, and Tamhane's T2 for differences in soil solution pH, P, and log Ca. $\alpha = 0.008$. See Table 4.6 for sample sizes.

Planned Comparison	pH	inverse Na	P	log Ca
H_{10}: B+S = B	0.731	1.000	0.989	1.000
H_{11}: B+S = S+T	1.000	<0.001	0.173	<0.001
H_{12}: B+S = T	1.000	<0.001	0.952	<0.001
H_{13}: B = S+T	0.194	<0.001	0.052	<0.001
H_{14}: B = T	0.190	<0.001	0.994	<0.001
H_{15}: S+T = T	1.000	1.000	1.000	0.966

* Planned and post-hoc comparisons pool data from the 2 years.

Table 4.9a Mean (standard error) of selected macronutrients and micronutrients in soil solution from Clear Lake trials. See Table 4.6 for sample sizes. Means within a row with the same letter in their superscript were not statistically different.† See section 4.2.5 and Tables 4.8a and 4.8b.

Variable and Year	Plot Identification					
	B+S	B	S+T	T	OL	CP
P (mg/L)						
1999	2.02(0.18)	2.69(0.24)	1.27(0.22)	1.60(0.35)	1.88(0.26)	1.84(0.68)
2000	1.28(0.22)	1.17(0.41)	0.27(0.17)	0.25(0.18)	0.56	0.88(0.25)
pooled*	1.71(0.20)	2.11(0.30)	0.94(0.20)	1.23(0.28)	1.38(0.26)	1.59(0.58)
K (mg/L)						
1999	7.71(1.81)	12.68(0.26)	6.17(0.60)	5.89(0.61)	6.58(0.82)	8.59(2.58)
2000	4.89(0.96)	6.27(1.64)	4.51(1.29)	4.54(1.72)	9.25	2.92(0.41)
pooled*	6.54(1.27)	10.22(1.73)	5.53(0.63)	5.54(0.68)	4.74(0.81)	8.86(1.88)
Ca (mg/L)						
1999	260.00(28.23)	216.12(34.64)	15.56(1.11)	25.90(4.56)	9.58(1.66)	22.94(10.50)
2000	218.85(55.91)	285.30(134.62)	15.77(1.40)	12.26(4.66)	25.13	4.38(0.84)
pooled	242.85(30.29)[a]	242.79(53.37)[a]	15.64(0.84)[b]	25.73(5.28)[b]	6.98(1.32)[c]	23.38(8.14)[b]
Na (mg/L)						
1999	11.09(1.90)	17.48(2.22)	4.75(0.43)	4.23(0.36)	3.29(0.29)	6.55(1.20)
2000	14.52(3.72)	28.11(11.19)	4.55(0.63)	4.66(0.39)	5.20	3.92(0.57)
pooled	12.52(2.05)[a]	21.57(4.48)[a]	4.67(0.34)[b]	4.42(0.27)[bc]	3.60(0.33)[c]	6.28(0.97)[b]
Mg (mg/L)						
1999	49.51(6.40)	53.55(7.35)	9.93(0.38)	13.52(1.44)	4.66(0.88)	9.97(2.98)
2000	49.53(14.29)	77.18(29.07)	7.64(0.76)	8.08(2.83)	8.25	3.01(0.29)
Mn (mg/L)						
1999	0.45(0.13)	0.89(0.26)	0.92(0.12)	1.33(0.74)	1.41(0.54)	0.39(0.17)
2000	0.17(0.09)	0.06(0.05)	0.19(0.13)	0.31(0.05)	0.02	1.15(0.35)
Fe (mg/L)						
1999	1.12(0.18)	1.44(0.19)	20.64(3.70)	25.11(10.08)	15.84(3.87)	21.11(11.69)
2000	0.38(0.17)	0.27(0.11)	6.14(1.66)	16.72(4.91)	1.99	32.50(3.13)

* There were no statisitically significant differences in Treatment for this variable.
† Pair-wise comparisons pool data from different years.

Table 4.9b Mean (standard error) of selected elements in soil solution from Clear Lake trials. See Table 4.6 for sample sizes.

Variable	Plot Identification					
and Year	B+S	B	S+T	T	OL	CP
Al (mg/L)						
1999	1.06(0.16)	1.20(0.24)	19.44(3.95)	23.29(8.91)	12.76(3.95)	29.24(16.70)
2000	0.21(0.09)	0.23(0.10)	2.31(0.55)	9.96(3.20)	1.76	20.30(1.63)
Cu (mg/L)						
1999	0.29(0.067)	0.28(0.034)	0.070(0.009)	0.081(0.016)	0.031(0.006)	0.10(0.021)
2000	0.21(0.042)	0.18(0.083)	0.014(0.003)	0.027(0.002)	0.018	0.017(0.004)
Cr (μg/L)						
1999	14.62(2.80)	17.28(1.86)	61.12(8.80)	77.71(25.46)	34.33(6.00)	67.69(28.22)
2000	1.07(0.94)	5.06(5.01)	16.03(2.67)	41.89(9.53)	7.56	37.79(4.00)
Ni (μg/L)						
1999	77.92(11.61)	85.12(8.57)	77.99(9.35)	105.97(24.50)	38.83(4.97)	87.89(22.03)
2000	2.71(0.76)	2.73(1.22)	1.26(0.30)	3.93(0.75)	1.26	3.19(0.14)
Zn (μg/L)						
1999	60.05(11.66)	70.21(9.23)	53.70(6.95)	88.78(18.04)	48.76(13.70)	110.80(31.01)
2000	22.33(6.68)	14.16(0.50)	12.01(2.36)	22.55(7.56)	9.32	22.55(7.56)
Cd (μg/L)						
1999	9.13(0.43)	10.06(1.09)	8.20(0.75)	12.16(2.20)	11.93(1.75)	11.52(2.13)
2000	below detection limits					

Table 4.10 Mean (standard error) of soil solution pH for 1999 and 2000, and mean (standard error)* of pooled soil solution pH data of the 2 years for soils from Clear Lake trials.

Year	Plot Identification					
	B+S	B	S+T	T	OL	CP
1999						
mean	7.26(0.12)	7.49(0.16)	6.41(0.16)	6.64(0.26)	5.59(0.11)	6.19(0.15)
sample size	5	8	8	8	4	4
2000						
mean	6.17(0.29)	6.81(0.20)	6.48(0.40)	6.42(0.95)	6.39(0.30)	6.50(0.38)
sample size	5	5	6	5	4	4
1999 and 2000 Pooled						
mean	6.72(0.23)^{ab}	7.23(0.15)^{b}	6.52(0.13)^{bc}	6.53(0.23)^{bc}	5.99(0.21)^{c}	6.10(0.15)^{ac}
sample size	10	13	14	13	8	8

* Means within a row with the same letter in their superscript are not statistically different. See section 4.2.5 and Tables 4.8a and 4.8b.

Table 4.11 Mean (standard error) of percent soil moisture content* for soils from Clear Lake trials.

	Plot Identification					
Year	B+S	B	S+T	T	OL	CP
1999						
mean	137.66(14.3)	123.94(26.0)	17.24(1.2)	19.82(1.2)	39.28(12.5)	82.47(54.8)
sample size	7	8	8	8	4	4
2000						
mean	75.75(18.3)	52.02(17.5)	17.17(1.0)	12.34(1.3)	23.26(2.5)	11.50(0.6)
sample size	8	8	8	8	4	4

* Percent soil moisture content was calculate as follows:

$$\%MC = \frac{\text{wet weight} - \text{dry weight at } 95°C}{\text{dry weight } 95°C} * 100$$

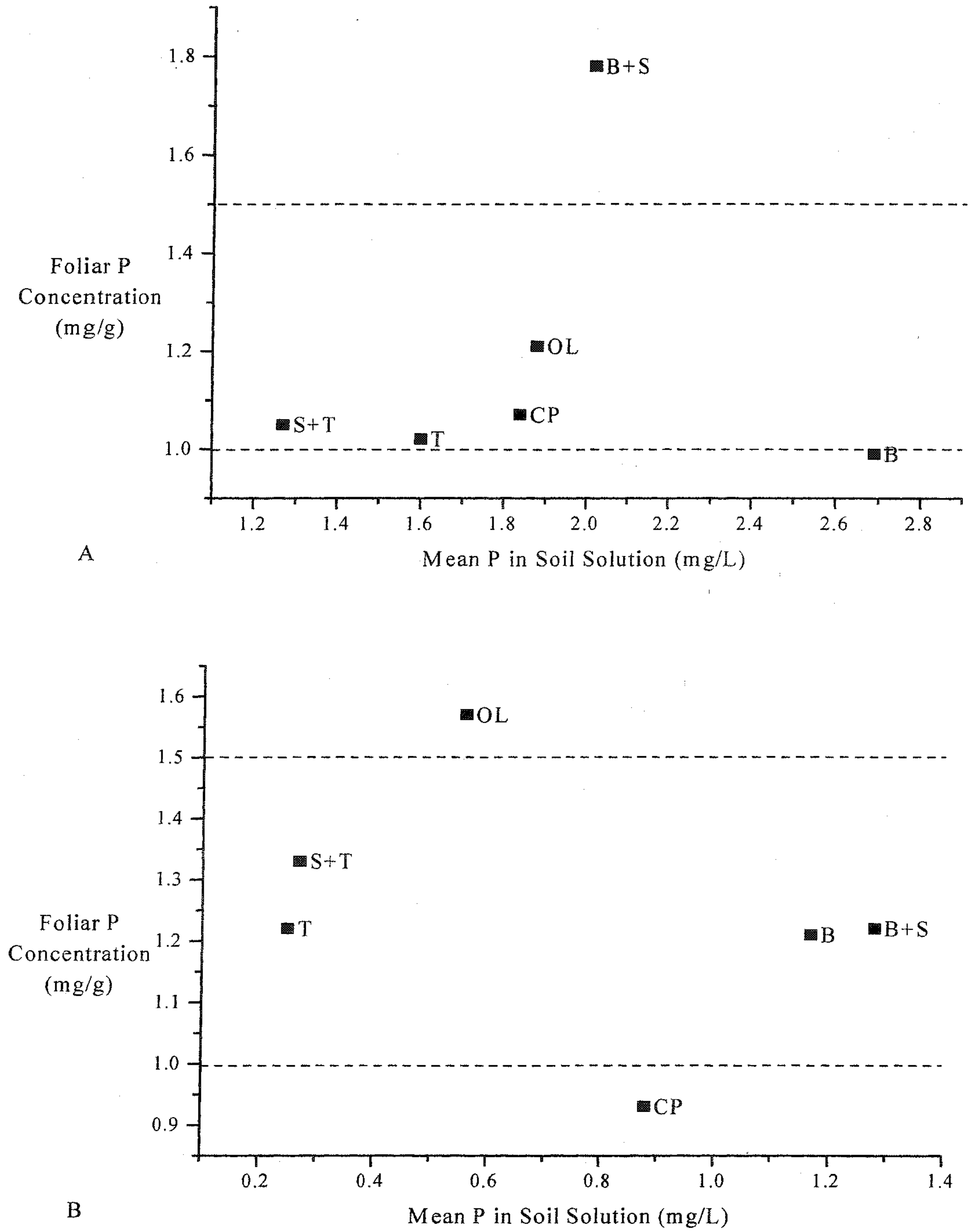
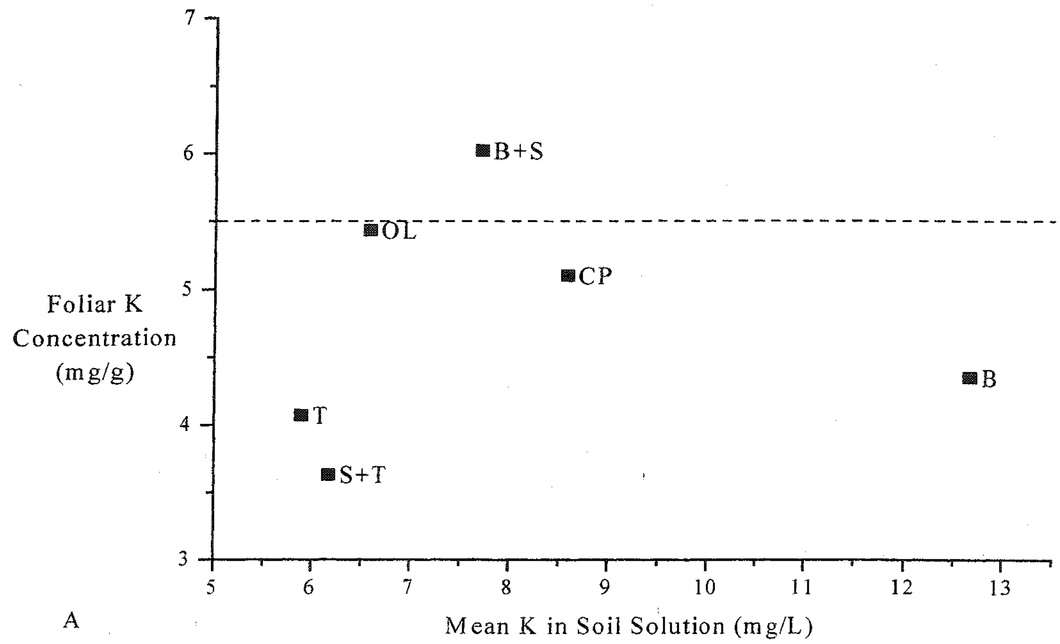


Figure 4.1 Comparison of P concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Bottom dashed line indicates threshold below which lodgepole pine is considered moderately deficient. Upper dashed line indicates threshold below which lodgepole pine is considered slightly deficient, above which it is considered adequate(Ballard and Carter 1986).



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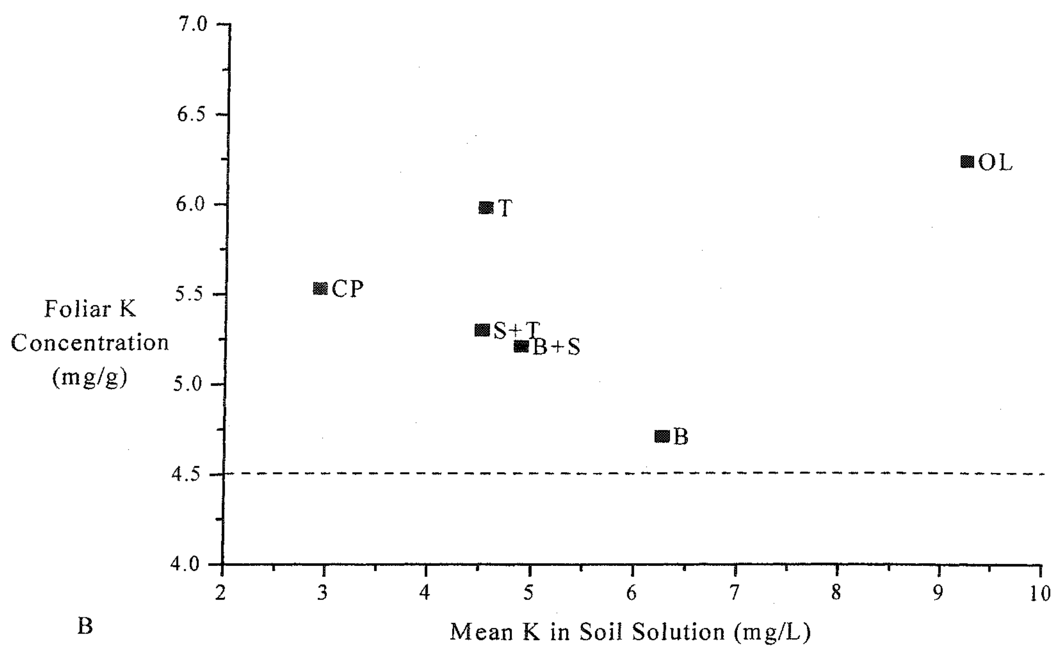

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Figure 4.2 Comparison of K concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Dashed line indicates threshold above which, and up to 7.5 mg K/g, indicates lodgepole pine K is slightly to moderately deficient (Ballard and Carter 1986).

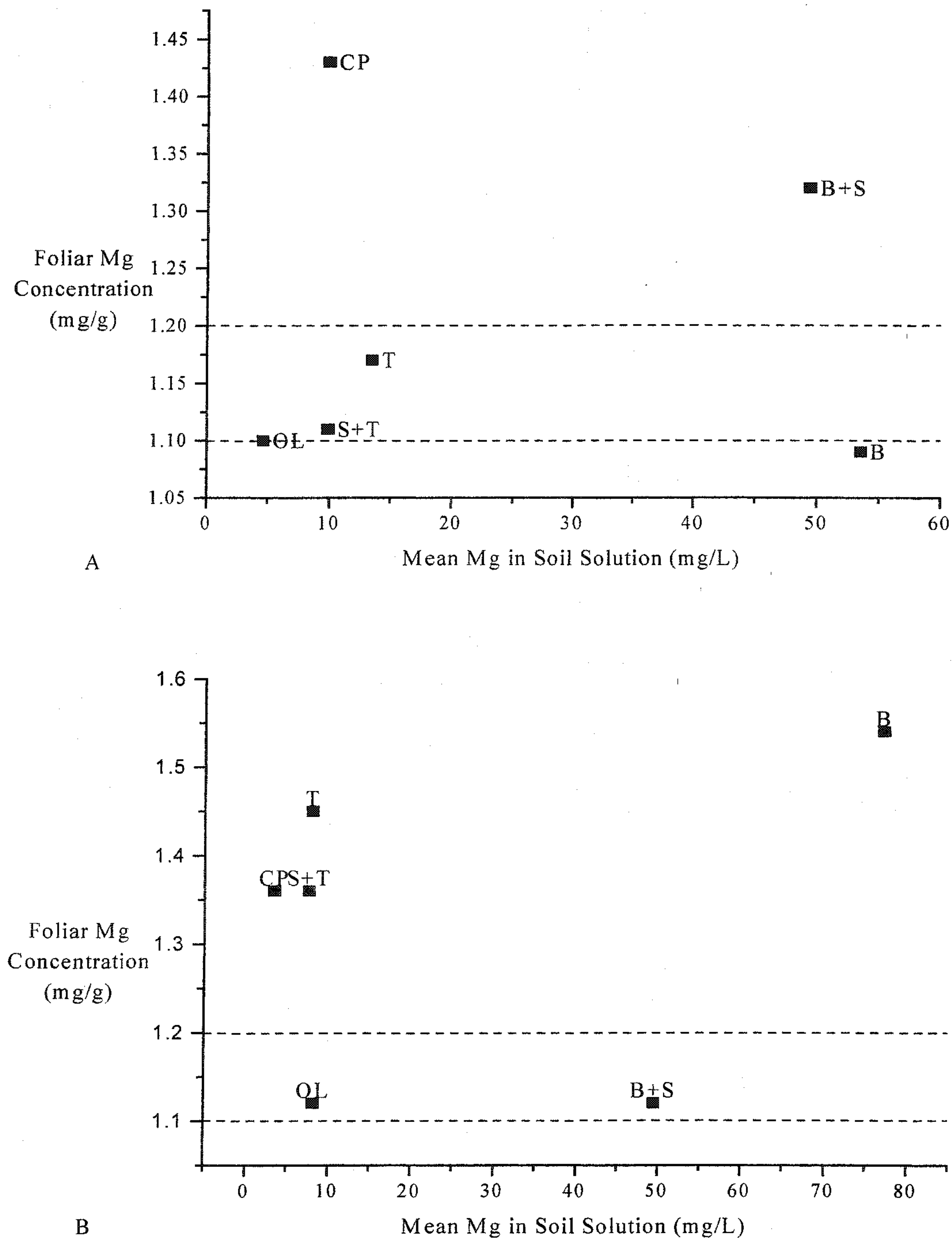


Figure 4.3 Comparison of Mg concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Bottom dashed line indicates threshold below which the possibility of lodgepole pine Mg deficiency is slight to moderate, above which lodgepole pine Mg deficiency is unlikely. Upper dashed line indicates threshold above which lodgepole pine Mg deficiency is not present (Ballard and Carter 1986).

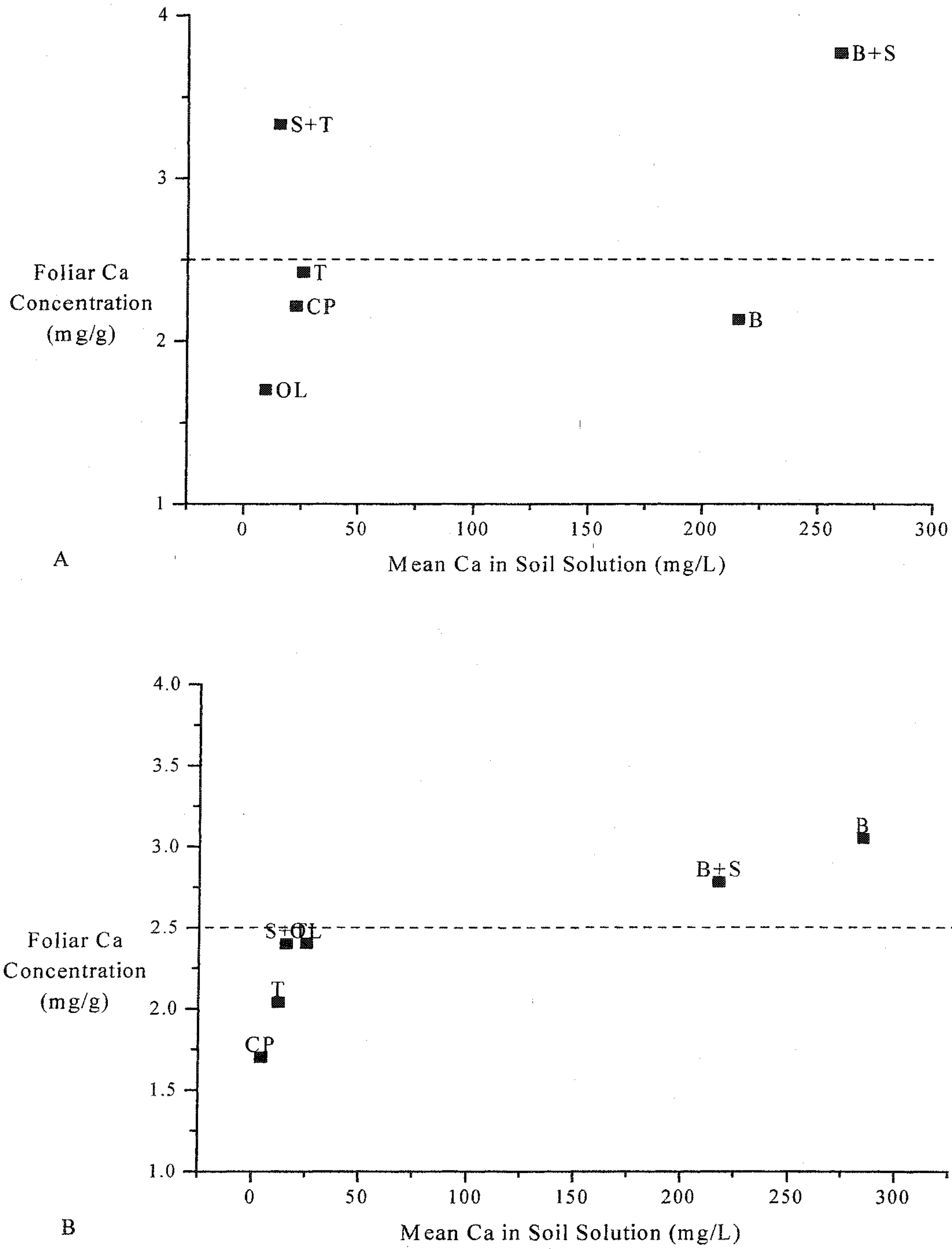


Figure 4.4 Comparison of Ca concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Dashed line indicates threshold above which lodgepole pine Ca deficiency is not present, below which Ca deficiency is unlikely (Ballard and Carter 1986).

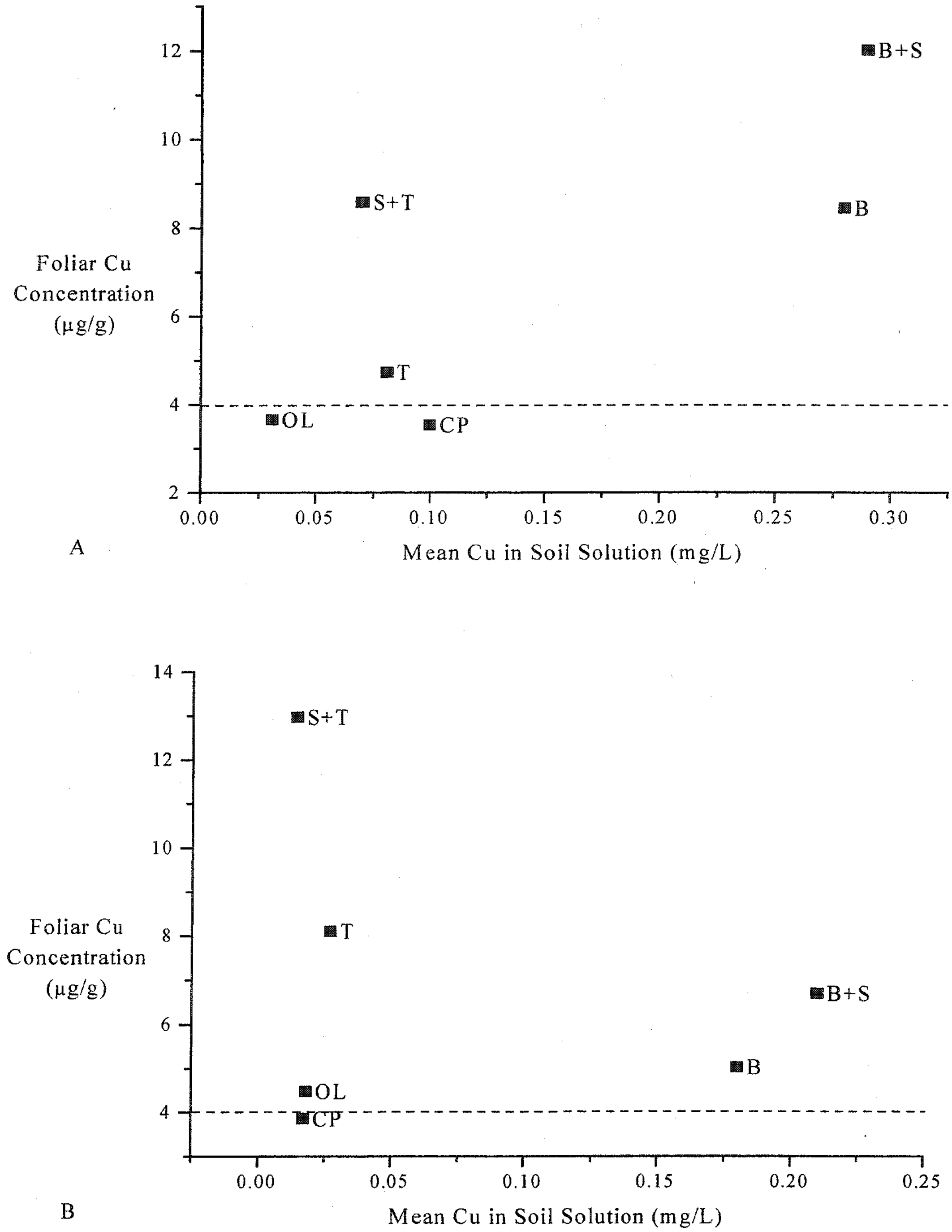


Figure 4.5 Comparison of Cu concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Dashed line indicates threshold above which Cu deficiency is absent for various conifers and below which Cu deficiency is unlikely (Ballard and Carter 1986).

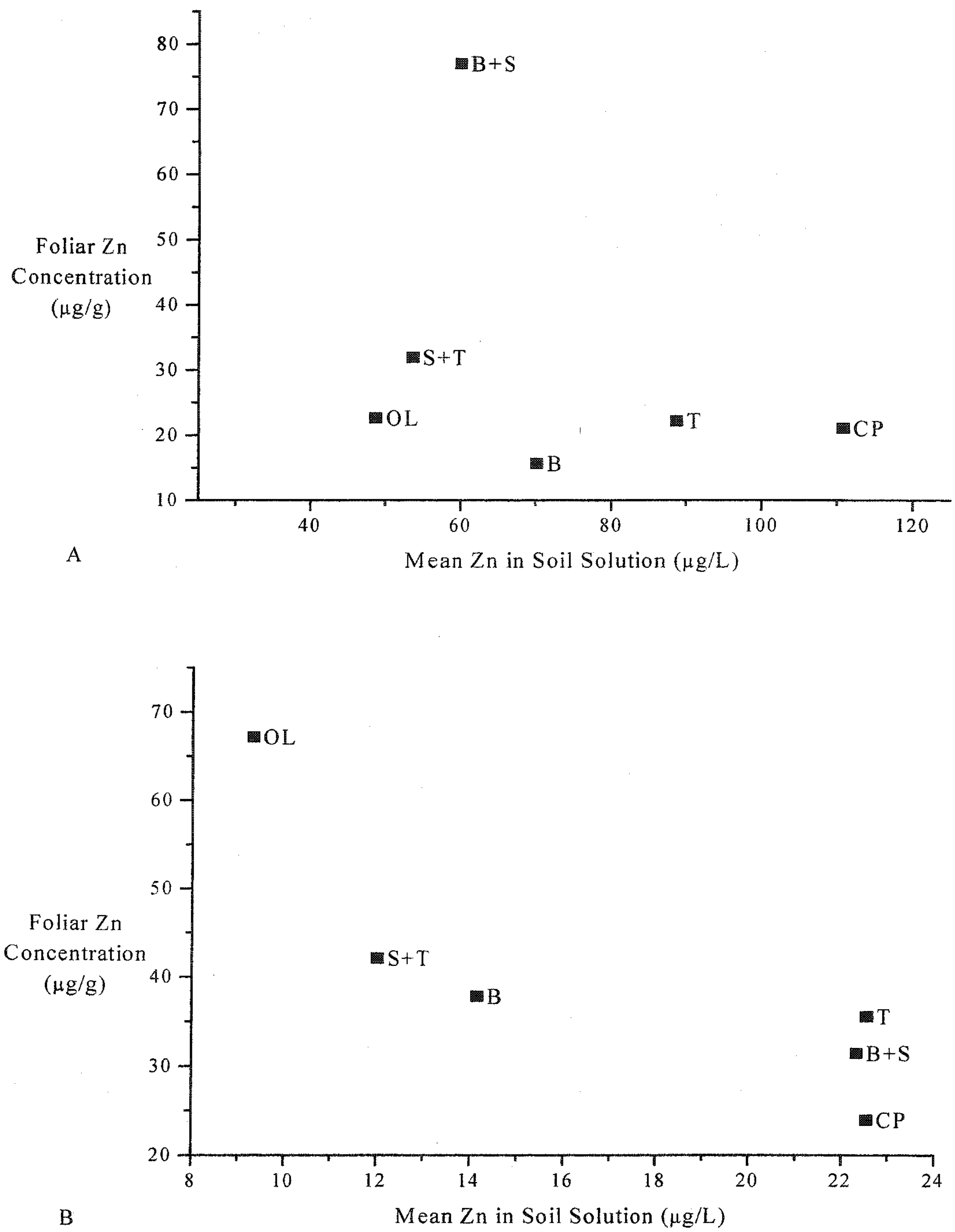


Figure 4.6 Comparison of Zn concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Above 15 µg Zn/g foliage, various conifers are not considered Zn deficient (Ballard and Carter 1986).

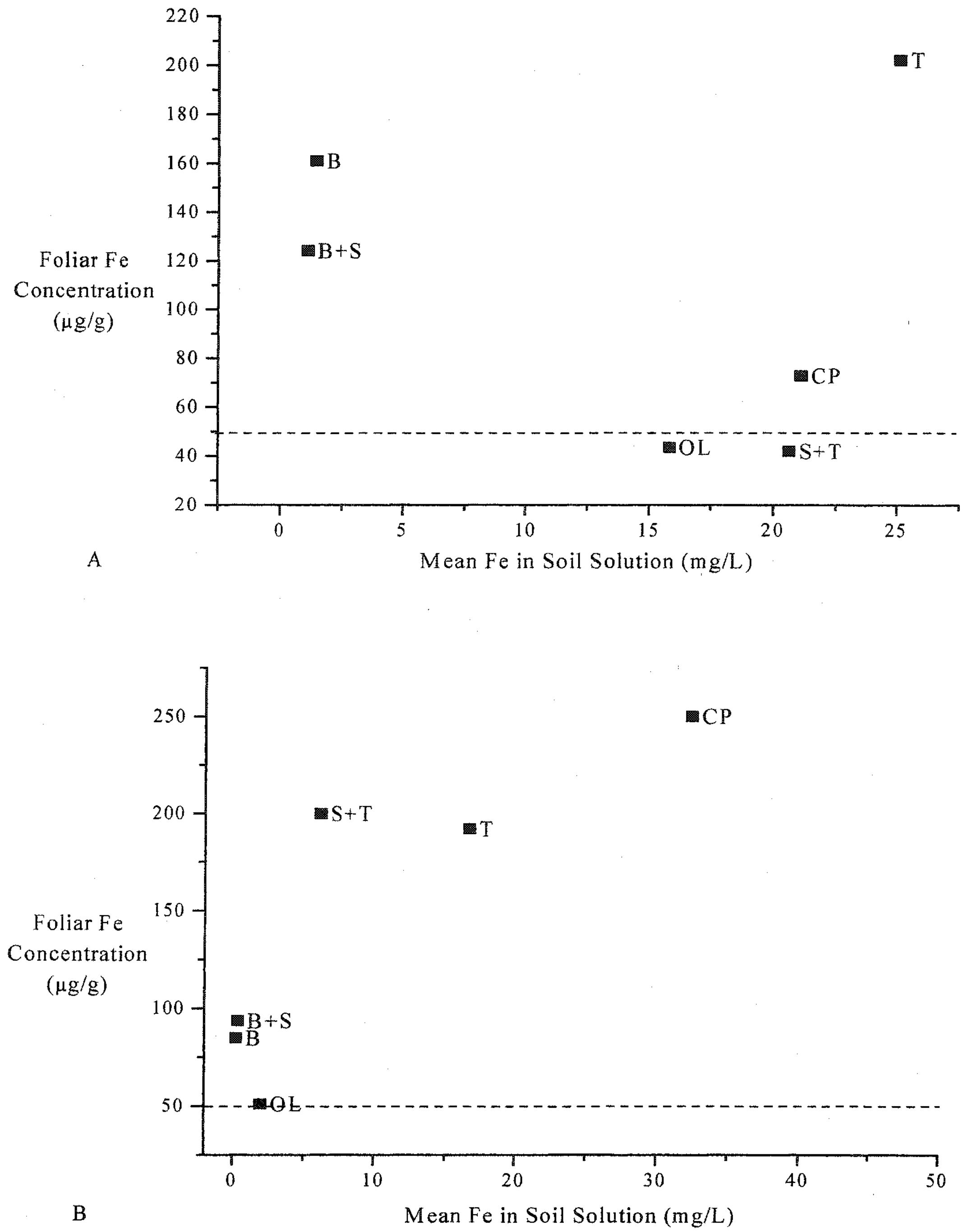
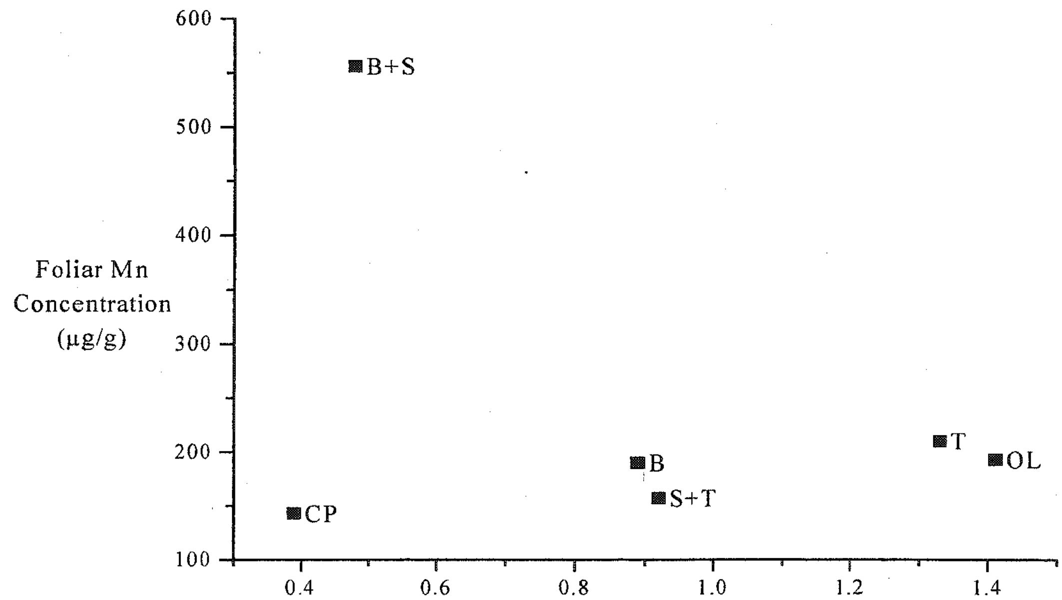


Figure 4.7 Comparison of Fe concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. Dashed line indicates threshold above which conifer Fe deficiency is improbable and below which deficiency is possible (Ballard and Carter 1986).



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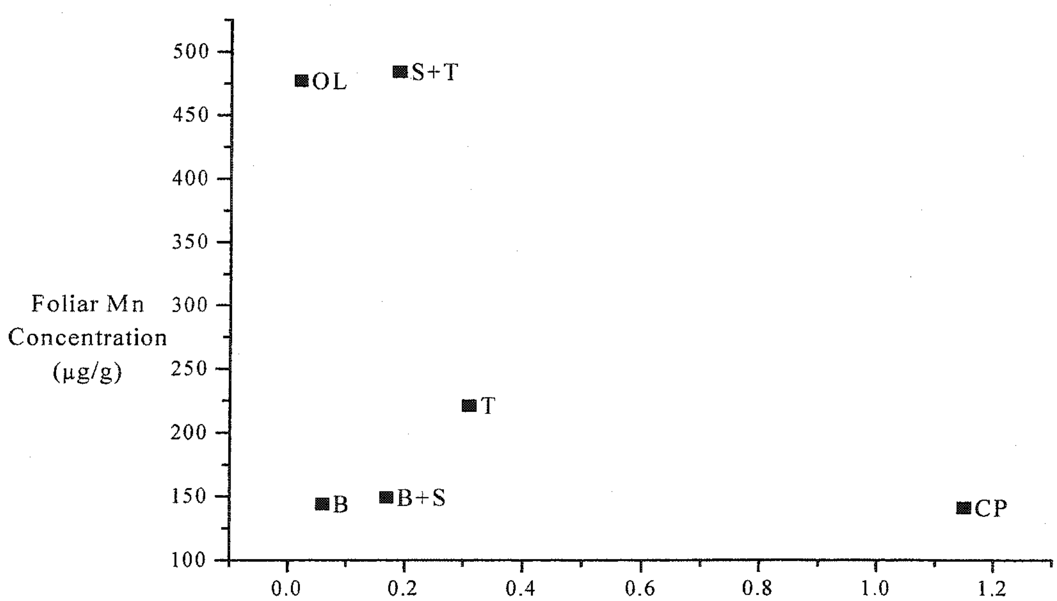

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Figure 4.8 Comparison of Mn concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes. All foliar Mn concentrations are well above the 25 µg Mn /g considered to represent the threshold for no conifer Mn deficiency (Ballard and Carter 1986).

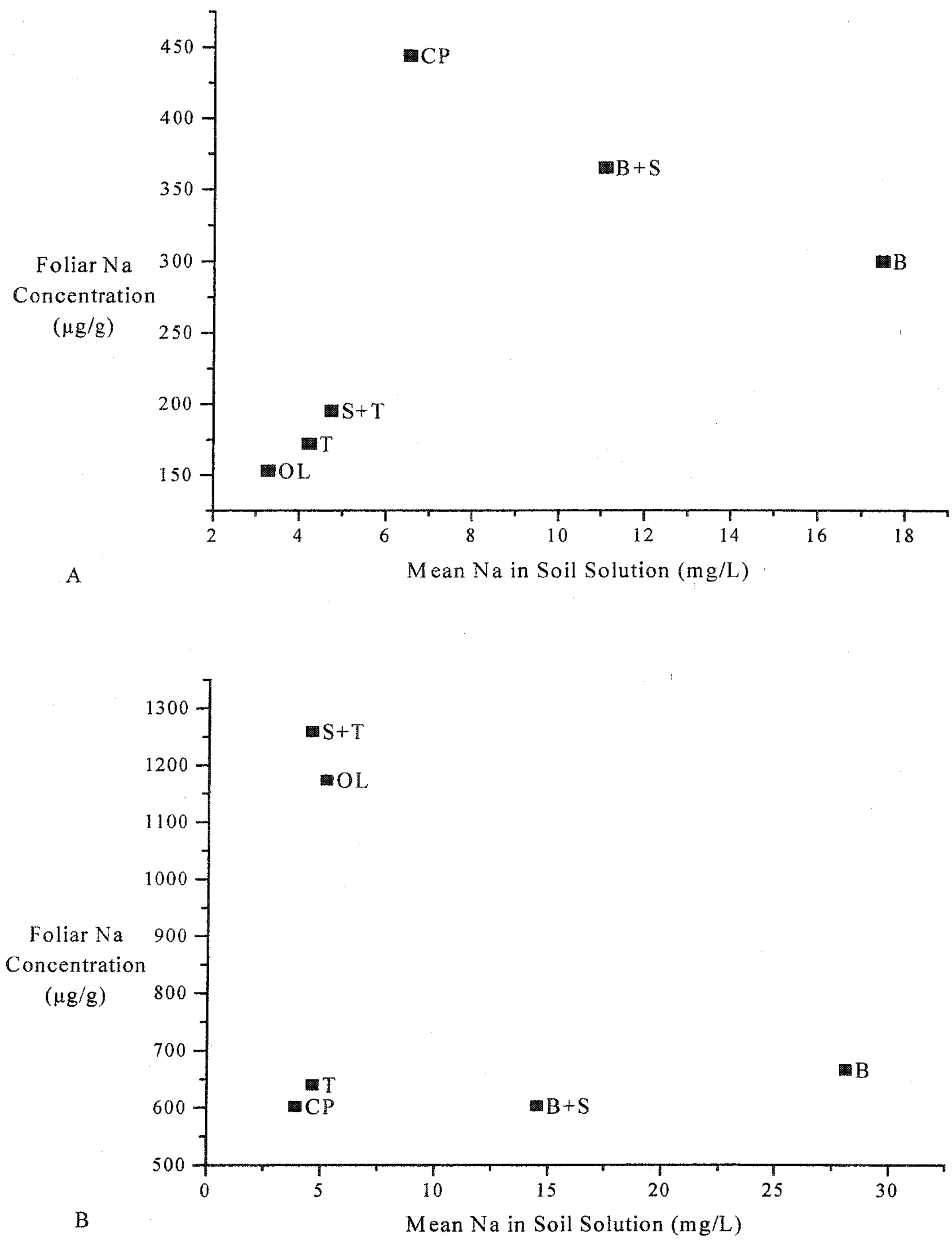
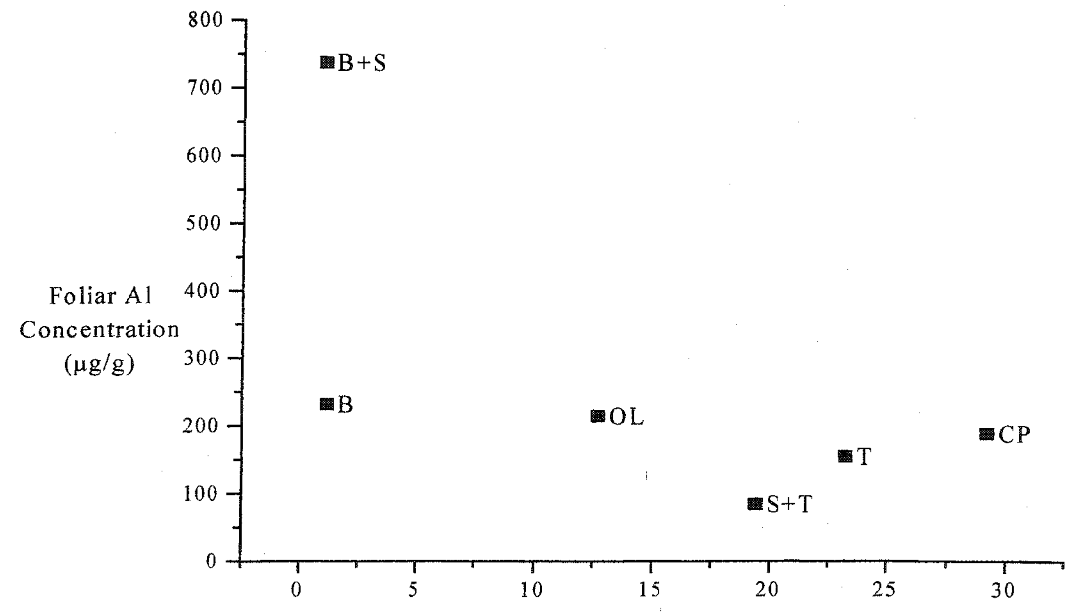


Figure 4.9 Comparison of Na concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites. See Tables 4.5 and 4.9 for sample sizes.



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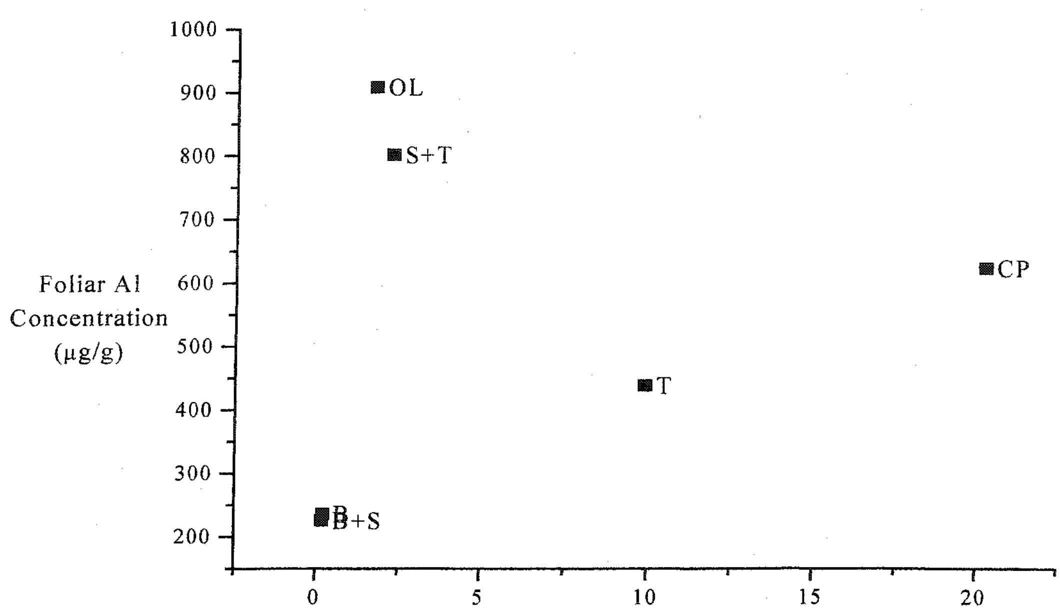

B

Figure 4.10 Comparison of Al concentration in lodgepole pine needles and in soil solution for experimental and reference areas of the Clear Lake sites.
See Tables 4.5 and 4.9 for sample sizes.

Chapter V -

Summary and Conclusions

5.1 Introduction

This chapter will summarize whether the research presented in this thesis met study objectives. Deciding whether the objectives were met will be based upon statistical analysis, discussion, and conclusions from Chapters III and IV. This final chapter will also provide management implications arising from the content of my study and recommendations for further study.

5.2 Study objectives

The objectives of the present study were: (1) to examine the effects of landing reclamation using tillage and biosolid application or tillage alone, with or without fallow legumes and grasses, on soil physical and chemical properties, and on seedling growth and foliar nutrient status; and (2) to measure the success of these reclamation techniques by comparing the resulting soil physical and chemical properties, seedling growth, and seedling foliar nutrient status with results from control areas.

5.3 Conclusions from analysis of soil physical and chemical properties

Differences between tillage-treatment, biosolid-treatment, control plot, and off-landing plot were identifiable for almost all of the soil properties statistically analyzed in Chapter III.

Statistical analysis illustrated that total K was largely unaffected by treatment, but that pH, ECEC, total P, total Ca, C:N and total Na of plots with biosolid treatment were significantly different from tillage-treated and control plots. Biosolid amendment did not change soil pH in comparison to tillage treatment, but did significantly elevate pH relative to control plots. Tillage-treatment was significantly different from reference plots only in pH and ECEC. The fact that total P and ECEC were significantly higher after biosolid application, and that C:N was significantly decreased after biosolid application, indicates that biosolid application did produce benefits for the compacted soil. Lack of significant differences between tillage-treated plots and control plots suggests that tillage alone was not an effective landing reclamation treatment.

5.4 Conclusions from soil solution composition

None of the paired comparisons for soil solution P showed a significant difference between plots, nor was soil solution K significantly different between treatments. Soil solution Na and Ca were significantly changed by biosolid treatment relative to control plots and tillage-treated plots. Ca in soil solution of tillage-treated plots was not significantly different from CP, and Ca in soil solution of tillage-treated plots was significantly lower than OL (this was the only significant difference between tillage treatment and control plots in soil solution properties); however, Ca and Na were not deficient in plant tissues and although these differences between plots were significant, they cannot be considered as indicators of whether soil solution composition was improved by landing reclamation. Soil solution pH was significantly changed by biosolid treatment relative to control plots, but not in comparison to tillage-treated plots; however, the range of soil solution pH observed in this study is within the optimum pH range where nutrient bioavailability is not restricted and potentially toxic elements are not readily mobilized (Brady and Weil 1999). Consequently, the soil solution data presented in this study cannot be used to establish that one reclamation technique was superior to another, nor that reclamation resulted in soil environments which were more favourable to tree growth than that of control plots.

5.5 Conclusions from seedling growth

After two growing seasons, biosolid amendment did not significantly change seedling height in comparison to seedlings grown on tillage-treated or reference plots, but seedlings planted on tillage-treated and unreclaimed landing plots were significantly shorter than those of an off-landing plot. Needle length was significantly shorter in seedlings grown on biosolid-treated while OL and T plots had the longest needle length. Basal diameter of seedlings planted on control plots was not significantly different from seedlings on tillage-treated plots, however, basal diameter of seedlings planted on biosolid-treated areas which were seeded with a fallow crop was significantly smaller that of control plots and tillage-treated plots. None of the treatments produced a significant change in leader height. Shoot weight was not statistically analyzed, however, B+S seedlings weighed half (or less than half) that of seedlings grown on all other plots. The success of tillage-plus-seeding treatment relative to tillage-only cannot be evaluated because of the failure of a cover crop to establish on the tillage-treated plots, however, it can be stated that tillage-treatment did not improve seedling height in comparison to an untreated control while biosolid treatment (without seeding) did improve seedling height in comparison to an untreated control. B+S was detrimental to seedling basal diameter and shoot weight and therefore was not a successful reclamation strategy.

5.6 Conclusions from foliar nutrient status

In Chapter IV, it was concluded that the seedlings in B+S plots were probably maintaining their foliar nutrient status by internally translocating nutrients. An example of a result supporting this conclusion is that no reductions in foliar nutrient status of B+S seedlings was readily evident in 2000, despite the fact that the seedlings appeared stressed. Statistical analysis of foliar nutrient status data was not conducted, however, it appeared that seedlings on biosolid treated plots without seeding had higher foliar concentrations of N than seedlings on tillage-treated plots. Foliar N status of CP seedlings was also high relative to other plots in 2000, while S+T had the lowest foliar N status. Comparing the foliar K of biosolid-treated plots to tillage-treated and to reference plots in 2000 indicated that the mineral soil of the tillage-treatment and reference plots was a better source of K than the biosolid-amended soil. All plots except CP and OL had approximately the same P status. CP had notably lower foliar P content and OL had notably higher foliar P content. On the basis of these observations, it is not possible to make a definitive statement regarding whether biosolid application or tillage treatment produced better foliar nutrient status. However, the fact that seedlings on tillage-treated plots generally had lower foliar concentrations of macronutrients than off-landing seedlings suggests that biosolid application treatments have more potential to supply nutrients over the long-term than do tillage-treated plots.

5.7 Overview of major conclusions

One of the most readily evident conclusions from this study is that seeding fallow legumes and grasses on biosolid-treated plots did not have a significant effect on any of the soil properties analyzed. On biosolid-treated plots with seeding, there was nearly 100% ground cover by grasses, hence the lack of significant differences between seeded and unseeded biosolid treatments was surprising; however, even a visual inspection of data from B+S and B treatments did not give the impression that the soil properties of the two sites were dramatically different. In the case of tillage-treated plots, the lack of significant difference between seeded and unseeded plots was due to the fact that the cover crop failed to establish. Data presented in Chapter III of this study, therefore, is inconclusive with respect to the benefits of seeding in landing reclamation.

Given that tillage did not appear to improve seedling foliar nutrient status over that of untreated landing plot foliar nutrient status, the final major conclusion from this study is that landing reclamation using biosolids (without seeding fallow legumes and grasses) has the best potential to produce better seedling performance in foliar nutrient status over the long-term. Therefore, biosolid amendment is expected to be found in follow-up studies to be a more effective reclamation strategy than tillage alone.

5.8 Management implications

Tillage was not found to be an adequate reclamation effort for the medium-textured soil studied herein. Given that Kranabetter and Osberg (1995) also found tillage and seeding to be ineffective, the available information on landing reclamation of medium-textured soil seems to support a recognition that organic matter amendment is necessary for successful rehabilitation of these sites.

Based on the conclusions of this study, seeding of grasses on biosolid-treated landings is detrimental to seedling growth because of the apparent competition and shading grasses cause, and because of the danger of snow press. If seeding after biosolid application is deemed necessary, then the species used in the seeding mixture must be low-growing.

Lastly, soil solution data from this study indicated that biosolid application did not cause a consistent potential threat of groundwater contamination. Any elements in soil solution which occasionally exceeded Health Canada (1995) guidelines for irrigation and livestock water were found to exceed the guideline on both control and treated plots. Therefore, biosolid application alone was not responsible for the elevated levels of these elements in soil solution.

5.9 Recommendations for further study

Growth of grasses on biosolid-treated plots presented considerable competition for the lodgepole pine seedlings in 1999 and 2000, whereas growth of naturally seeded in species was negligible in 1999 and represented approximately 85% ground cover in 2000. This study was not long enough to ascertain whether naturally regenerating herbs and grasses would snow press the lodgepole pine seedlings in 2000 and on, hence it is recommended that a longer study (i.e., 4 to 5 years) be made comparing low-growing fallow crop with natural regeneration of local vegetation on biosolid-treated plots in order to determine which method presents the least risk to the survivorship of tree seedlings.

It is difficult to assess how well a reclamation technique will perform many years after treatment on the basis of short-term results. Research funding is seldom guaranteed for more than a few years at a time, hence it is important that indicators of long-term success that can be measured on a short-term basis be found. Unfortunately this study failed to successfully evaluate one such indicator, seedling root structure, partially due to the labour-intensive nature of obtaining and analyzing samples. Future study of root growth and morphology of plants on landing reclamation sites would be beneficial in further understanding of the effect of reclamation on overall plant growth.

Future studies would also be enhanced by the inclusion of a minimum of three replicates of each treatment and control plot type, with all landings having being constructed at the same time and in the same manner (i.e. full or partial bench), having a similar soil type, and using amendments which are uniform in their characteristics (i.e., composted or land stored amendments used in a given study are from the same stockpile and the stockpile is mixed as much as possible prior to land application).

Given that groundwater contamination issues are of critical importance, a study should be done to confirm the conclusion that biosolid application does not pose a threat to groundwater on these study sites. A study to validate this conclusion should include samples taken by lysimeter, or other soil solution sampling device, from 30 cm or deeper in the soil profile.

5.7 Literature cited

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Health Canada. 1995. Canadian Water Guidelines: Summary of guidelines for water quality in Canada. Environment Canada, Ottawa. Pamphlet.

Kranabetter, J.M. and M. Osberg. 1995. Landing reclamation trials in the Prince George Forest Region. Prepared for the Prince George Forest Region. Unpublished. 10p.